

Faculteit Industriële  
Ingenieurswetenschappen

master in de industriële wetenschappen:  
elektromechanica

Masterthesis

"Design and implementation of a sustainable solution for upgrading and distributing  
biogas in rural Tanzania."

Kenneth Dries  
Louis Macours

Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: elektromechanica

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2024  
2025

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# Preface

During spring 2023, as young engineering students, we attended a seminar hosted by Prof. Deferme on the influence of climate change on water management in rural Africa. In addition to the keynote speakers, some students presented the master thesis they conducted in Kenya. This inspired us to try to do a similar project.

Motivated by that seminar, we explored similar initiatives in Africa. Professor Deferme then walked us through the local context and highlighted several ongoing projects, particularly in Dar es Salaam, Tanzania. Here, several projects around waste-to-resource take place. One of these projects, Emmanuel Nsekela's Ph.D., focused on improving biogas usability. With our engineering background, we were a good fit to support his work by exploring purification and compression of biogas.

First and foremost, we would like to express our sincere gratitude to Prof. Dr. Ir. Wim Deferme for his invaluable support from the very beginning of this journey. His guidance, expertise, and unwavering encouragement played a crucial role in shaping this international experience in Tanzania and elevating the quality of our project.

We also extend our heartfelt thanks to our external supervisor, Dr. Nyangi Chacha. As a lecturer at Arhdi University, her insights into biogas and her organizational support were of great significance to the success of this project.

We would also like to thank Mr. Emmanuel Nsekela for the support and guidance during the first months of our stay in Tanzania. Also Mr. Elisha Yusuph Jackson helped us greatly during and after our stay in Tanzania.

This master's thesis is part of a 10-year development collaboration between the University of Arhdi and Hasselt University. We are grateful to everyone involved in this partnership who helped make this project possible, as well as VLIR-UOS for their assistance.

Our sincere thanks also go to all those who contributed financially by participating in our fundraiser. Your generous support created additional opportunities and helped take our project to the next level. We also thank Students for Energy in Africa (S.E.A.) for their time and support.

Finally, we would like to thank our families, friends, and partners for their support and continuous trust. Sharing this experience with you has meant a great deal to us, and in challenging times, your presence was a constant source of strength and comfort.



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# Glossary

**Absorption** A process in which a substance is taken up into the volume of another substance, such as a gas being absorbed into a liquid.

**Activated carbon** A porous material used for filtering and purifying gases or liquids by adsorbing impurities, widely used in water treatment and gas scrubbing, in a low quality it is also known as char.

**Anaerobic digestion** A biological process where microorganisms break down organic matter in the absence of oxygen, producing biogas and sludge.

**Capital expenditure (CAPEX)** The upfront costs incurred to acquire, build, or upgrade physical assets such as buildings, machinery, or energy systems. These are one-time investments made at the start of a project.

**Depth of Discharge (DoD)** A measure of how much energy has been used from a battery, expressed as a percentage of the total battery capacity. For example, a DoD of 80% means 80% of the battery's energy has been discharged. Managing DoD is important for extending battery life and performance.

**Direct normal irradiance (DNI)** The amount of solar radiation received per unit area by a surface that is always held perpendicular (normal) to the sun's rays. It is a key metric for assessing the potential of solar energy systems, especially concentrating solar power (CSP) technologies.

**Discounted cash Flow (DCF)** A method that evaluates the value of an investment based on its expected future cash flows, discounted back to their present value.

**Discounted payback Time (DPT)** The time it takes for an investment to recover its initial cost, considering the time value of money.

**Feedstock** Raw materials (such as organic waste, manure, or crops) used as input for processes for biogas combustion to produce energy or other products.

**Fixed-dome digester** A biogas system with a non-movable, dome-shaped structure where gas is stored under pressure and displaces slurry into an overflow tank.

**Floating-drum digester** A type of biogas plant where the gas is collected in a movable, floating gas holder that rises and falls based on gas production.

**Kariakoo** A commercial area in Dar es Salaam, Tanzania, known for its markets and trade activities; often a hub for wholesale goods.

**Kimbi** The location of the Ardhi university testing site and a ward in Kigamboni, Dar es Salaam.

**Levelised Cost of Energy (LCOE)** The average cost per unit of energy produced over the lifetime of a project, accounting for installation, operation, and maintenance costs.

**Maximum power point tracking (MPPT)** A method used in solar power systems to optimize the power output by continuously adjusting the operating point of solar panels to extract maximum energy.

**Moisture trap** A device used to remove water vapor or liquid water from gas streams by locally expanding the gas to prevent corrosion and improve efficiency of downstream equipment.

**Net present Value (NPV)** The difference between the present value of cash inflows and outflows over a project's lifetime, used to assess profitability.

**Operational expenditure (OPEX)** The ongoing costs required to run and maintain a system or business, including labor, maintenance, utilities, and consumables. These are recurring expenses over the project's lifetime.

**Power with modulation (PWM)** A technique used to control the power supplied to electrical devices by rapidly switching the power on and off, adjusting the average voltage or current.

**PVCU (Unplasticised Polyvinyl Chloride)** A rigid and durable form of PVC commonly used in construction for pipes and fittings due to its chemical resistance and strength.

**Removal efficiency** A measure of how effectively the treatment system removes specific pollutants, expressed as a percentage.

**Sludge** A semi-solid byproduct from anaerobic digestion, containing water, organic matter, and microorganisms.

**Tanzanian Shilling (TZS)** The official currency of Tanzania, the project employs this currency. The rate is TZS 3,034.78 equals EUR 1 (on 08/06/2025).

**Water scrubbing** A method used to clean gas (e.g., biogas) by passing it through water, which absorbs impurities like carbon dioxide.

# Abstract

Access to sustainable and clean energy remains a critical challenge in Tanzania, where reliance on traditional biomass sources such as wood and charcoal contributes to adverse health outcomes and environmental degradation. Biogas from organic waste offers a sustainable alternative but requires purification and compression to improve cooking efficiency and enable distribution. This thesis designs a solar-powered system to purify and compress biogas generated in Kimbiji. Here, an anaerobic digester produces approximately 100 L of gas per day with 35% carbon dioxide ( $CO_2$ ) and 260 ppm hydrogen sulfide ( $H_2S$ ). This work aims to reduce  $CO_2$  to 25% and  $H_2S$  to 5 ppm.

A test setup was constructed to test suitable purification methods under local conditions. Two  $CO_2$  removal methods were compared: absorption using calcium hydroxide ( $Ca(OH)_2$ ) and water scrubbing. For  $H_2S$  removal, four local adsorbents were tested, including (rusted) steel wool, iron oxide and activated carbon.

For the Kimbiji setup,  $Ca(OH)_2$  absorption is used for  $CO_2$  removal, while rusted iron wool is selected for  $H_2S$  removal. Here,  $CO_2$  was reduced to 16% and the final  $H_2S$  level was 2 ppm. To enable distribution, the gas is pressurized to 8 bar using solar energy and stored in LPG cylinders.

A techno-economic analysis indicated that small-scale purification entails a levelized cost of 1,581 TZS/kWh, rendering it not viable. However, a large-scale system, proposed in this work, able to process 6,500 L biogas per day, proved economically viable with a cost of 145 TZS/kWh.





# Abstract in Dutch

Toegang tot duurzame energie blijft een uitdaging in Tanzania, waar het gebruik van traditionele biomassa zoals hout en houtskool bijdraagt aan gezondheidsrisico's en milieudegradatie. Biogas uit organisch afval biedt een alternatief, maar moet gezuiverd en gecomprimeerd worden om de kookefficiëntie te verbeteren en distributie mogelijk te maken. Deze thesis ontwikkelt een systeem om biogas, geproduceerd in Kimbiji, te zuiveren en te comprimeren. Daar produceert een anaerobe vergister ongeveer 100 l gas per dag met 35 % kooldioxide ( $CO_2$ ) en 260 ppm waterstofsulfide ( $H_2S$ ), wat moet reduceren tot 25 %  $CO_2$  en 5 ppm  $H_2S$ .

Een testopstelling aan Ardhi University bood de mogelijkheid om verschillende zuiveringstechnieken te vergelijken. Twee  $CO_2$ -verwijderingsmethoden werden getest: absorptie met calciumhydroxide ( $Ca(OH)_2$ ) en waterscrubbing. Voor de  $H_2S$ -verwijdering werden vier lokale absorberende materialen getest.

Voor de opstelling in Kimbiji zijn  $Ca(OH)_2$ -absorptie en verroeste ijzerwol voor  $CO_2$ - en  $H_2S$ -verwijdering gekozen. De  $CO_2$  concentratie bereikt 16% en het  $H_2S$ -gehalte daalt tot 2 ppm. Om distributie te realiseren, wordt het gas gecomprimeerd tot 8 bar met zonne-energie en opgeslagen in LPG-tanks.

Een techno-economische analyse toont dat kleinschalige biogaszuivering leidt tot een genivelleerde kostprijs van 1 581 TZS/kWh, wat niet rendabel is. Voor een groter systeem, in dit werk voorgesteld om 6 500 l biogas per dag te verwerken, bleek de kost slechts 145 TZS/kWh. Dit evenaart de lokale alternatieven.



# Chapter 1

## Introduction

Access to reliable and clean energy remains one of the most pressing challenges facing rural communities in Africa [1]. Particularly in sub-Saharan Africa, where the electricity infrastructure is limited and reliance on traditional biomass sources such as charcoal and firewood persists [2], [3]. In these areas, the majority of households depend on traditional biomass fuels such as firewood and charcoal for cooking, lighting, and heating [4]. Although these sources are inexpensive and widely available, they are associated with significant adverse outcomes [5], [6]. Indoor air pollution caused by inefficient combustion of biomass contributes to respiratory diseases, especially among women and children who spend prolonged periods near cooking stoves [7]. Globally, the World Health Organization estimates that indoor air pollution leads to over 3 million premature deaths annually, with Sub-Saharan Africa being one of the most affected regions [8].

Beyond health impacts, the reliance on firewood and charcoal contributes to both environmental and ecological degradation, including deforestation, global warming, loss of biodiversity, and soil erosion [6]. This has further socio-economic consequences, such as reduced agricultural productivity and increased labor demands on locals who must travel longer distances to gather firewood. As energy demand increases with population growth, the need for sustainable and scalable alternatives becomes even more critical, especially now that the Tanzanian government has put a ban on firewood and charcoal [9]. This challenge is further compounded by rising energy costs and the lack of infrastructure in rural areas to support electricity distribution or alternative energy systems [10], [11]. Meanwhile, Tanzania, like many other countries in the region, generates large volumes of organic waste, particularly agricultural and municipal residues. This waste remains largely unutilized, often left to decompose in open fields or landfills [12] where it releases methane, a potent greenhouse gas that contributes to climate change.

The conversion of organic waste, including municipal waste and other biodegradable materials, to biogas offers a cleaner and more sustainable energy alternative [13]. Anaerobic digestion, the process underpinning biogas production, effectively utilizes organic waste to generate renewable energy while mitigating greenhouse gas emissions and reducing reliance on fossil fuels [14]. The implementation of waste-to-energy technologies, such as biogas production from organic waste, has significant potential to contribute to sustainable energy development, particularly in developing countries, addressing environmental

and energy challenges [15]. Biogas production from agricultural residues and other organic waste represents a significant opportunity for sustainable energy generation. Biogas can replace a significant portion of energy consumption [16]. By harnessing bio-waste, biogas offers dual environmental and energy benefits.

## 1.1 Anaerobic digestion: process and benefits

Anaerobic digestion is a biological process where microorganisms break down organic matter in an oxygen-free environment [4]. This process yields two valuable products: biogas and digestate. Biogas primarily consists of methane ( $CH_4$ ) and carbon dioxide ( $CO_2$ ), with trace amounts of other gasses such as hydrogen sulfide ( $H_2S$ ) and ammonia ( $NH_3$ ). Methane, the combustible component, is the key to energy generation [4], while the digestate, rich in nitrogen and other nutrients, can be used as a high-quality organic fertilizer [17]. This fertilizer provides an opportunity to enhance agricultural productivity while reducing reliance on chemical fertilizers, which are often expensive and environmentally damaging.

The anaerobic digestion process involves several key stages [18]:

1. Hydrolysis: The breakdown of complex organic materials into simple sugars, amino acids, and fatty acids by enzymes;
2. Acidogenesis: The conversion of these simpler molecules into volatile fatty acids, ammonia, and hydrogen by fermentative bacteria;
3. Acetogenesis: The production of acetic acid, carbon dioxide, and hydrogen from the volatile fatty acids;
4. Methanogenesis: The final stage where methanogenic bacteria convert acetic acid and hydrogen into methane and carbon dioxide.

Temperature stability is crucial for the efficiency of this process. Mesophilic digestion<sup>1</sup>, which occurs at temperatures between 30-40 °C, is commonly used because it is less sensitive to temperature fluctuations and easier to maintain, especially in warmer climates like in Tanzania, as solar irradiation is a sufficient energy source [18]. When relying on solar irradiation, the digestion process becomes highly dependent on external weather conditions [19].

The gas mixture can be used for cooking [4] or for local electricity production [20]. However, raw biogas produced during anaerobic digestion requires treatment before it can be used effectively [21]. Impurities such as  $CO_2$ ,  $H_2S$ ,  $NH_3$ , and water vapor must be removed to improve the energy content and usability of biogas.

## 1.2 Current setup

Ardhi University, a key partner in this project, is conducting research to optimize biogas production and enhance its usability. The university operates multiple working digesters

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<sup>1</sup>Other options include psychrophilic and thermophilic digestion, these digestions occur at 10-20 °C and 50-60 °C respectively.

across different sites, two of which will serve as implementation locations for this project. The first site, located in the university’s experimental hall, is the primary hub for research and testing. The second site, situated in Kimbiji, a ward in the Kigamboni municipality approximately 40 km from Dar es Salaam, will allow for testing under real-world conditions.

### 1.2.1 University setup

The setup at the university consists of two floating-drum digesters composed of a 1,000 L and a 800 L tank each, as seen in Figure 1.1. The system is supplied with corn husks during three days a week. During each feeding, a mixture of approximately 1 kg of dry biomass is combined with 10 L of water before being fed into the reactor. The system is capable of producing approximately 50 L of biogas per day. In addition, electricity and water are readily available at this location.



Figure 1.1: Current setup at Ardhi University

Located in the Experimental Hall, this setup functions as a hands-on teaching platform for Ardhi University. It enables local students to design and run their own experiments, deepening their practical understanding of biogas production processes, system performance evaluation, and data analysis.

The purpose of this setup for this thesis is to provide a test platform close to the university to evaluate the technical viability of purification and compression techniques under realistic conditions. Insights gained from this phase will guide the refinement of the Kimbiji system to ensure an optimal design and optimize its practicality and sustainability.

### 1.2.2 Kimbiji setup

The Kimbiji setup, as seen in Figure 1.2, serves as a larger test site where multiple projects are carried out simultaneously. It is located within a local community, this community will be directly involved in the the project by supplying the organic waste and as primary users of the produced biogas. In addition to a digester, this setup also includes a sorting facility where organic trash and glass can be sorted. Relying on the community for feedstock and maintenance poses a challenge, as knowledge and skills related to biogas are limited. However, overcoming this challenge significantly enhances the value of the

project, making it a valuable example for future similar biogas projects. The Kimbiji site consists of two distinct setups.

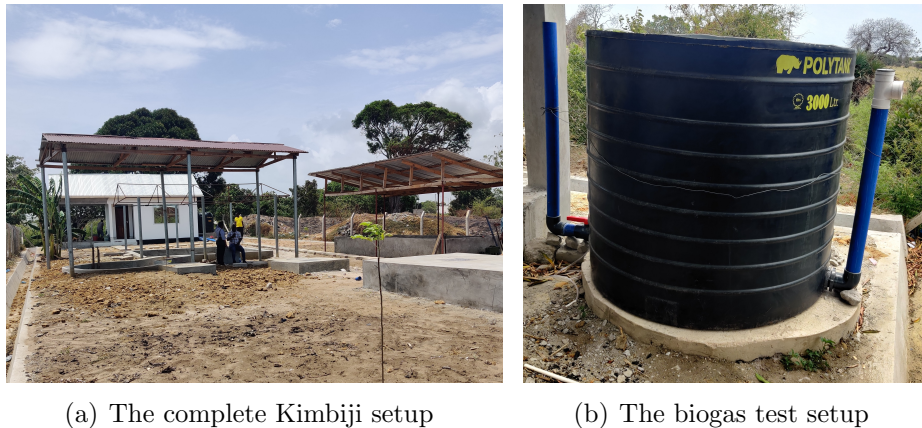


Figure 1.2: The Kimbiji test site

Both digesters operate by breaking down local organic waste, such as crop residues or other kitchen wastes, as well as fecal organic matter. The ratio between these different waste types, along with specific operating conditions, is an area of ongoing research in various projects at the site, making the input composition for this project variable. To minimize manual labor, one of the digesters is placed partially underground. By doing this, gravity will automatically fill the digester with feedstock. This design also helps maintain a stable temperature, which is essential for the efficient activity of anaerobic microorganisms responsible for the production of biogas [22].

### Sludge Processing setup

The first setup, depicted in the foreground of Figure 1.2, focuses on processing the waste by-product of biogas production, namely sludge. Ongoing research aims to convert this sludge into high-quality fertilizers. The design of this setup includes a mixing chamber and an activation chamber. Subsequently, the material is fed by gravity into a digester, where biogas is produced. After this biogas is extracted from the digester, the remaining sludge is then transferred to a sludge drying bed, where it undergoes drying before it can be used as fertilizer.

Originally, the plant was designed with a 18,000 L fixed-dome digester capable of delivering 6,500 L of biogas per day. However, after budget cuts, a 3,000 L floating-drum digester was installed. This project will implement a system that works on the smaller-scale setup so that it can be used and tested in the current setup. However, at the end of Chapter 5 this thesis proposes a design capable of handling the original capacity.

### Biogas Optimization System

This project will be working on the second setup. This setup, illustrated in Figure 1.2(b), is dedicated to optimizing the calorific value of biogas. By adjusting the input composition, researchers at Ardhi University aim to enhance the quality of the produced biogas. This setup consists of a 3000 L tank with a 2000 L floating-drum on top. It represents a more cost-effective alternative to the fixed-dome design.

The extracted biogas flows from the digester through a moisture trap to remove excess water from the gas stream. It then passes through a desulfurizer to eliminate  $H_2S$  before reaching a gas flow meter, after which it can be extracted and stored.

During this project, the digester was fed with a combination of kitchen waste, grass and leaves. 75% of the contents was kitchen waste, including fruit shells, vegetable and leftovers. The remaining 25% of the contents is grass and leaves. This setup is expected to produce approximately 100 L of biogas per day.

### 1.3 Problem statement

Despite their potential, biogas systems face several challenges that limit their efficiency and scalability. The raw biogas output contains a high concentration of impurities, including  $CO_2$ ,  $H_2S$ ,  $NH_3$ , and water vapor. These impurities significantly reduce the usability of the biogas [4]:

- Carbon Dioxide: The high  $CO_2$  content lowers the calorific value of biogas, making it less effective as a fuel for cooking and heating;
- Hydrogen Sulfide: A toxic and corrosive gas,  $H_2S$  damages metal components in appliances and storage tanks, increasing maintenance costs and reducing system longevity [23], [24];
- Ammonia: While less corrosive than  $H_2S$ ,  $NH_3$  contributes to unpleasant odors and can harm end-users if not properly removed [25];
- Water Vapor: Moisture in biogas causes condensation during compression and storage, leading to corrosion and reduced durability of infrastructure.

In contrast to the university setup, the Kimbiji setups lack running water and electricity. Although an electricity line passes through the Kimbiji village, this line is not connected to the test setup. This means any proposed solution must operate independently of the national electricity grid, further emphasizing the need for a self-sustaining and locally adaptable design.

Since the local community supplies the organic waste, its quality and composition can vary, affecting both the quantity and quality of biogas production. A lack of proper waste sorting can also lead to non-organic materials entering the digester, disrupting its efficiency. Additionally, the remote location of the site presents logistical challenges for the project.

In addition, the low-pressure nature of the current system, typically around 1 bar, restricts the storage and transport of biogas, necessitating direct consumer connections, as storage and transport at low pressure is impractical. This limitation hinders scalability and flexibility, making it challenging to distribute biogas beyond local use.



A final issue relates to the maintenance of the installation. When the local population starts using the installation, it is important that it is easy to operate, and that clear instructions are provided. Furthermore, any defects must be easy to fix, which means the components of the installation should be locally available or manufacturable. This will also facilitate the reproduction and scalability of the installation should a new site be developed.

## 1.4 Objectives

This thesis aims to design and implement a sustainable solution for upgrading and distributing biogas in rural Tanzania. By integrating renewable energy into the biogas purification and compression processes, this project presents an adaptive and innovative approach to biogas utilization. Two designs will be developed: one for the test setup at the university and one for the site in Kimbiji. Figure 1.1 shows the university setup, and Figure 1.2(b) shows the Kimbiji setup. This project will focus on the biomass test setup. The Kimbiji setup will need to process approximately  $0.10 \text{ m}^3$  of unfiltered gas every day. Both designs must be fully developed, implemented and analyzed by the end of the master's thesis.

The first major objective of this project is to purify the biogas by removing undesirable gas fractions to achieve a higher methane concentration. A methane concentration of at least 75% is targeted to ensure efficient use for cooking and heating applications [26]. Additionally, adequate removal of water vapor is essential to prevent excessive liquid water formation during the compression and storage stages.

Furthermore, the amount of  $SO_2$ ,  $H_2S$  or  $NH_3$  present in the final product should be sufficiently low so as not to pose health risks. This means the mixture should not contain more than 500 ppm of  $NH_3$  and no more than 5 ppm of  $H_2S$  [25], [23].

The second major objective focuses on developing a solution to compress the gas mixture, raising the biogas to a higher pressure. This pressure must be high enough to enable practical distribution of the gas. Furthermore, during use, the pressure should be sufficiently high to ensure that the compressed gas remains usable for an adequate period. This pressure level guarantees that the biogas can be conveniently stored in cylinders and transported to end users.

The compression and filtration system must be powered entirely by renewable energy, this ensures that the system can be implemented at the Kimbiji setup or any other remote, off grid location. To guarantee consistent operation even during adverse weather conditions, a battery system may be incorporated. The energy system will be designed to ensure sufficient power generation to sustain the entire biogas purification and compression process.

In addition to the implementation and validation of the Kimbiji setup, a theoretical design, made to handle the 6,500 L per day should be proposed. This design will serve as guidance for the future expansion of the Kimbiji site.

Another critical component of this project is evaluating its economic feasibility, which involves assessing the cost-effectiveness of the proposed designs. This analysis should cover both capital and operational expenses, including costs for materials, renewable energy

infrastructure, maintenance, and the implementation of the biogas digester. Scalability also has to be discussed, as the proposed solution may be implemented at different scales in other projects. The design will have to ensure it is financially viable for the local community.

Additionally, the community should be able to operate and maintain the installation after the project is concluded. Therefore, a user manual should be included. The design will utilize materials and components that are either locally available or can be produced locally. In this context, locally means components that are manufactured or sold in Tanzania, or that can be easily imported. This ensures an accessible implementation.

A final objective is to establish collaboration with the local community in Kimbiji, facilitating the exchange of information. This collaboration will be crucial for gaining insight into their practices and needs. It will also be essential for the local community to acquire an understanding of the concept and its implementation, enabling them to correctly use and maintain the system, ensuring longevity of the system.

## 1.5 Method

The first step of the project involved a literature review aimed at acquiring in-depth knowledge on the subject. This provided insights into the most suitable techniques for this project. The literature review primarily focused on methods for separating methane from other gas fractions. Additionally, it examined approaches for efficient compression and distribution of the gas. Lastly, the review considered the use of renewable energy, exploring options for implementation and the potential need for battery storage. Different potential approaches were evaluated and eventually combined into one clear concept.

Based on this concept, a detailed design was developed. The design takes the technical and logistical constraints of both test setups into account. In this phase, both the technical and economic feasibility of the design were assessed, and a economical model is developed. Additionally, it was determined which components and materials are locally available and which will need to be imported.

In the next phase, the design is implemented in Tanzania. The test setup at the university was realized first to gain insight into the strengths and weaknesses of the design. If necessary, the design could be adjusted where needed to address any shortcomings and to optimize performance. There is no need to implement the energy part in this phase yet, as the setup is supplied by electricity and water.

Ultimately, the full, modified design, including sustainable energy source, was implemented at the site in Kimbiji. Once build, the installation was tested and evaluated to assess the purity of the produced gas, the energy consumption of the system, and the final gas pressure. These results will be crucial for further optimization of the system and for understanding the efficiency, functionality and scalability of the design.

During the implementation and testing phases, collaboration with the local community was needed to gain insight into the local situation and to provide instructions on usage and maintenance. This ensures that the installation can continue to be operated and maintained after the implementation stage.

After the implementation and validation at the Kimbiji setup, a design for a larger scale version of the installation was developed. As a final step, a techno-economical analysis (TEA) was performed to compare the viability of upgraded biogas against other sources of energy. The economical analysis also compared the feasibility of the small-scale setup and large-scale setups.

## 1.6 Contribution to sustainable development

This research aligns with global sustainable development goals (SDGs) [27], particularly SDG 7 (Affordable and clean energy), SDG 13 (Climate action), and SDG 15 (Life on land). By addressing the dual challenges of waste management and energy access, the project aims to:

- Reduce reliance on environmentally damaging fuels such as firewood and charcoal, thereby mitigating deforestation and global warming;
- Improve public health by reducing exposure to indoor air pollution;
- Provide rural communities with knowledge and technology to sustainably manage their energy resources;
- Transform organic waste to an energy resource by the implementation of waste-to-energy technology;
- Provide a cheap, local alternative for expensive energy.

Additionally, the fertilizer produced as a byproduct of anaerobic digestion can offer a significant contribution to agricultural productivity, reducing the need for synthetic fertilizers and supporting sustainable farming practices.

## 1.7 Structure of this thesis

This thesis is organized to examine the development and feasibility of a sustainable, community-based approach to biogas production and distribution in rural Tanzania. The structure progresses from foundational research to practical insights and recommendations.

The first section presents a literature review, offering an in-depth analysis of biogas purification and compression technologies, renewable energy integration strategies, and distribution methodologies. This review provides theoretical and contextual grounding for the study.

Next, the design phase focuses on the detailed development of a biogas purification and compression system tailored to the specific needs of the Kimbiji community and the university environment. This phase bridges theory and practice by contextualizing the design within these unique settings.

The University setup chapter outlines the practical execution of the system on a smaller scale, presenting the test results and detailing subsequent refinements made to enhance performance and efficiency.

These refinements are then implemented at the Kimbiji test site, where the system is exposed to more rural conditions. The project's validation in this environment is documented in the Kimbiji setup chapter. In this chapter, a larger design will also be proposed, to handle the 6,500 L fixed-dome digester in the future.

Following this, the economic analysis evaluates the system's economic viability, scalability, and potential for replication in other rural contexts. This analysis underscores the broader applicability and sustainability of the proposed solution.

Finally, the thesis concludes with Conclusions and recommendations, summarizing the key findings, addressing challenges encountered during the research, and providing directions for future work in this field.

By integrating these components, the thesis aims to demonstrate the feasibility of a sustainable biogas production and distribution model that not only benefits the Kimbiji community, but also offers a scalable framework for similar rural initiatives. The insights gained through this research are expected to contribute meaningfully to the advancement of renewable energy solutions in underserved regions.



# Chapter 2

## Literature review

This chapter reviews the existing literature on biogas upgrading and distribution systems, forming the foundation for developing a scalable and efficient solution tailored to the project's requirements and constraints. By analyzing technological advancements, best practices, and operational challenges, it provides the groundwork for the design and implementation of the project.

The literature review will focus primarily on four areas: upgrading of the biogas, compression of the upgraded biogas, distribution of the compressed biogas and the need for renewable energy to power the upgrading and compression processes. Upgrading the biogas includes removing water and  $H_2S$ , as these components could degrade the compressor and can be dangerous to humans [23].

The input for the system is the gas mixture produced by the biogas digester. It primarily consists of methane, carbon dioxide, and hydrogen sulfide. While trace amounts of other gasses such as hydrogen, oxygen and nitrogen may also be present, they are negligible in comparison to the main components [4].

By upgrading the biogas, its combustion efficiency can be significantly improved. Typically the Methane concentration of biogas is below 70%, this number however varies depending on the input and time. The project aims to achieve a methane concentration of 70% or higher, as this ensures optimal combustion [26], while not over perusing high quality as this can significantly increase costs [28]. However, other components in the gas should also be removed or minimized. For instance, hydrogen sulfide, a toxic gas, needs to be reduced to a maximum recommended level of 5 ppm in the final product to comply with safety standards [23]. Additionally, to prevent water formation in the compressor, it is essential to remove sufficient water vapor ( $H_2O$ ) from the biogas.

Compression is a key process to enable transportation and utilization of biogas at other locations. By compressing the gas, more energy can be extracted from the same volume, and thus facilitates transportation. The project targets a final pressure of 8 to 10 bar [29]. Critical considerations in this process include energy efficiency, maintenance requirements, lifespan and the structural design of the system.

These processes require energy to function. Since the Kimbiji site lacks access to the electrical grid, it is necessary to provide an alternative energy source. The literature review will explore the best way to supply power, as well as the potential use of batteries for energy storage.

The ultimate goal of the project is to upgrade, compress and distribute biogas to the local community in Kimbiji. Therefore, the literature will briefly examine distribution methods for biogas.

The conclusion of the literature review will identify the most suitable technologies for use in the project, based on efficiency, feasibility, scalability, and applicability.

## 2.1 Upgrading

Table 2.1 presents the typical composition of biogas. However, this composition is highly dependent on the input feedstock used in the gas production process, as well as the time after the input was added and the ambient temperature.

Table 2.1: Concentration of various components in biogas [4, p. 26]

| Component        | Symbol | Concentration (Vol-%) |
|------------------|--------|-----------------------|
| Methane          | $CH_4$ | 55-65                 |
| Carbon Dioxide   | $CO_2$ | 35-45                 |
| Water            | $H_2O$ | 2-7                   |
| Hydrogen sulfide | $H_2S$ | 20-20000 ppm (2%)     |
| Nitrogen         | $N_2$  | <2                    |
| Oxygen           | $O_2$  | <2                    |
| Hydrogen         | $H_2$  | <1                    |
| Ammonia          | $NH_3$ | <0,05                 |

As shown in Table 2.1, the methane concentration can be as low as 55% in the worst-case scenario. It must be increased to enhance the energy content of the biogas. When the methane concentration falls too low, the combustion efficiency decreases and the energy the system delivers is insufficient for cooking or heating purposes [30]. A significant amount of  $CO_2$ , the second largest fraction of the gas, will need to be removed to increase usability. As previously mentioned, it is also best to remove water vapor before the compression stage to prevent the formation of liquid water, which could adversely affect the system's performance and lifespan.

Additionally, this project aims to remove  $H_2S$  from the gas, as it is toxic and must be reduced to a concentration of 4 ppm to meet both safety and natural gas standards [23], [31]. Nitrogen, hydrogen, and oxygen are present in biogas only in trace amounts and have a negligible impact on its combustion properties. Therefore, these gasses will not be considered in detail in this literature review.

Finally,  $NH_3$  is present in the gas mixture. To meet safety standards, the concentration of  $NH_3$  must remain below 500 ppm [25]. In the typical gas mixture, the  $NH_3$  content is

below 0.05% or below 500 ppm, which is below the safety threshold. As a result, this minor gas fraction will be excluded from further analysis. During the project’s implementation phase, it should be tested and confirmed that the ammonia levels are indeed below the safety threshold.

The following sections will examine various techniques for upgrading biogas. The first group of methods, adsorption, Pressure swing adsorption, absorption, and cryogenic separation, are capable of removing  $CO_2$ ,  $H_2S$ , and  $H_2O$  from the gas. The next group, water scrubbing and biological removal, can remove  $CO_2$  and  $H_2O$ . Membrane separation is effective for the removal of  $CO_2$ , and finally, the physical drying method is specifically used to remove water from the gas.

### 2.1.1 Simultaneous removal of $CO_2$ , $H_2S$ and $H_2O$

#### Adsorption

Adsorption method relies on the principle that  $CO_2$ ,  $H_2S$ , and  $H_2O$  are adsorbed by certain solid materials. In this technique, biogas is passed through a column containing a solid adsorbent, typically in the form of coarse granules. When the unwanted gas fractions come into contact with these granules, they are absorbed [32]. In some situations, adsorption can even be used inside the digester. This method, however, is sensitive to moisture and can reduce the effectiveness of the adsorption material.

A significant advantage of adsorption is its selectivity, allowing it to target one or more specific gas fractions. For instance, it can be tailored to remove only  $H_2S$  by using materials such as rusted steel wool or to remove water with silica. This flexibility makes it easy to combine with other techniques [33].

To remove  $H_2S$  specifically, iron salts can be integrated directly into the anaerobic digestion stage [34]. However, while this approach is effective, it is often cost-prohibitive and can negatively impact the digestion process by influencing pH and reaction temperature [35].

While initial implementation costs for this method are relatively low, operational expenses are higher due to the frequent replacement of the absorbent material. These costs can be mitigated through material regeneration. However, adsorption is often labor-intensive and sometimes involves exothermic reactions that risk spontaneous combustion. Indicators for regeneration can vary: the material may show changes in color or texture, while in other cases, the need for regeneration is only detectable through output biogas analysis. Despite regeneration efforts, the material’s original properties cannot be fully restored, requiring complete replacement after several cycles. This technique is often employed as a precursor or post-process stage for other methods [32], [35].



## Pressure swing adsorption

Pressure Swing Adsorption (PSA) is a technique in which biogas is passed through a tank filled with solid adsorbent material, typically activated carbon or zeolites. This material selectively removes components such as  $CO_2$  and  $H_2S$  from the gas. Once the adsorbent material becomes saturated, it can be regenerated by lowering the pressure in the tank and exposing it to ambient conditions to release the adsorbed fractions [36]. A principle sketch is given below in Figure 2.1.

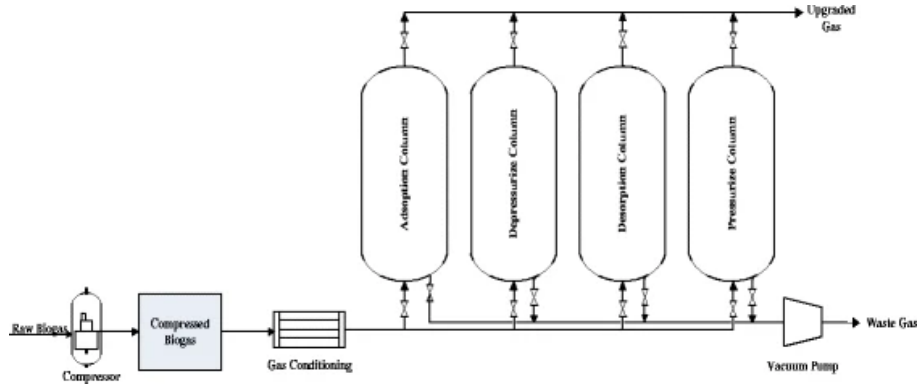


Figure 2.1: Principle sketch of PSA [36, p. 1920]

Typically, four tanks operate in parallel to provide a more continuous operation, with each tank in one of the following phases: adsorption, depressurization, desorption, and pressurization. The system generally operates at pressures of 8-10 bar. A related technology, Vacuum Swing Adsorption (VSA), utilizes a vacuum pump to accelerate the desorption stage.

The process involves a high capital investment and often requires expensive control systems to ensure smooth operation. Additionally, there is typically significant gas loss during depressurization, leading to a portion of the  $CH_4$  being removed from the system. For optimal performance, the system requires very dry biogas to prolong the life of the adsorbent material. However, it offers a compact setup with minimal space requirements and is insensitive to fluctuations in input gas composition, making it more suitable for implementation on a small-scale [35], [37].

## Absorption

This technique employs chemicals to dissolve carbon dioxide. The biogas is pressurized and is directed from the bottom to the top of a tank, where an alkaline or glycol solution flows in the opposite direction. It is crucial to optimize the gas-liquid contact surface in this process.  $CO_2$ ,  $H_2O$ , and  $H_2S$  dissolve in the solution and are thereby removed from the gas. The resulting biogas can achieve a  $CH_4$  purity of up to 97%. The liquid can be regenerated by passing it through another tank where air is blown through it. The use of chemicals minimizes evaporation losses, and compared to water, these chemicals are more effective at absorbing  $CO_2$ , thus requiring a smaller volume [38].

Alkaline solutions are often effective for small-scale setups due to their cost-effectiveness and operational simplicity. Commonly used materials, such as calcium hydroxide and

sodium hydroxide, are widely available in local markets. However, a significant drawback is that the resulting waste products are typically non-regenerable and require proper disposal, which can pose environmental challenges [35].

Using glycol solutions is more efficient than water-based methods due to the smaller volume that needs to be circulated. Additionally, there is no need for an extra step to remove water vapor from the system, as it dissolves in the solution. However, the initial investment and maintenance costs are high due to the use of specialized chemicals, although this is less of an issue when using amines. In some situations,  $H_2S$  may not be effectively filtered out of the gas. Absorption is generally used by systems with high flow rates, as it is more expensive to operate [32], [35], [39].

Alternatively, amines can be employed for this process. In this method, the biogas does not need to be pressurized. However, the regeneration step requires steam or heat, which would make the system design significantly more complex and energy inefficient [40].

## Cryogenic separation

Cryogenic separation is a technique in which biogas is separated by cooling the gas at elevated pressure, allowing it to reach a stage where liquid  $CO_2$  can be separated from the remaining methane gas. This process first requires that the gas is compressed to 80 bar, which is achieved in several stages with the use of an intercooler. Subsequently, the gas is cooled to  $-45\text{ }^{\circ}\text{C}$ . At this point, the liquid  $CO_2$  can be separated from the gas, though it still contains a small fraction of dissolved methane. The liquid  $CO_2$  at high pressure and low temperature can then be expanded, this will form solid  $CO_2$  which is a waste product of the process. In addition to  $CO_2$ , this technique also removes  $H_2S$  and water vapor from the biogas resulting in the final product consisting of 90% to 97% methane and is more efficient when more  $CO_2$  is present in the unfiltered biogas [32], [41].

The process involves high capital and operating costs. Therefore, this technique is most economically viable when implemented on a large industrial scale. Additionally, the technique is energy-intensive due to the high levels of compression and deep cooling required. However, if the goal is to produce liquefied biogas, this technique offers advantages as it requires relatively little additional energy to transition from cold, high-pressure biogas to its liquefied phase. The process is also environmentally friendly, as it does not rely on chemical solvents and requires no additional materials other than energy to operate [35]. This technique is ideal for larger plants that require a high purity [42].

### 2.1.2 Simultaneous removal of $CO_2$ and $H_2S$

#### Water scrubbing

Water scrubbing operates on the principle that different gasses have varying solubilities in water. Biogas is pressurized to 10 bar and then passed through a tank where water flows in the opposite direction. This tank, the adsorption column, should aim to maximize

the gas to liquid contact surface for an optimal solubility. Due to  $CO_2$  being 26 times more soluble in water than methane, it is selectively removed from the gas. This process also removes  $H_2S$  and other minor fractions. The final product is biogas with a methane concentration of 97%. A principle sketch is given in Figure 2.2 [35], [43].

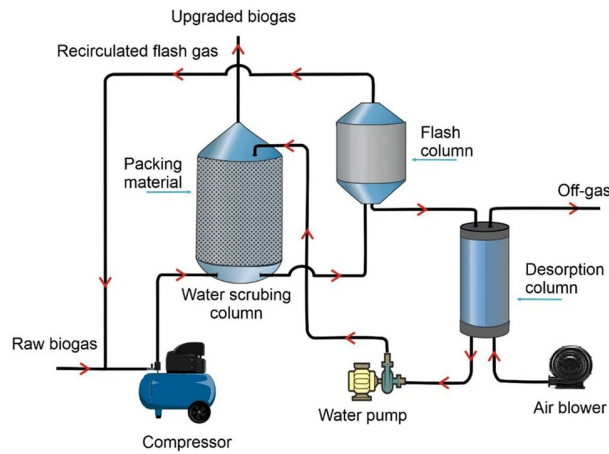


Figure 2.2: Principle of water scrubbing [35, p. 4139]

The water used in the process can be regenerated by mixing it with air at low pressure. However, a small portion of methane also dissolves in the water, resulting in a loss of approximately 4%. These losses can be minimized by employing multiple stages during the regeneration process. It is necessary to replace the water regularly, as sulfide accumulates in the solution, reducing its capacity to absorb other substances [35].

To minimize methane losses in the system, a flash tank can be added. This flash tank operates at a lower pressure than the adsorption column, reducing the solubility of the gas in the liquid, causing a portion of the gas to separate from the liquid. The separated gas can then be recycled back into the system's input. For further optimization, some implementations utilize multiple flash tanks. However, this approach requires a higher initial investment and is not viable for this project [35], [44].

Alternatively, the process can be conducted at near atmospheric pressure. Although this initially consumes less energy, it is generally as efficient as high-pressure water scrubbing because more water is required to extract the same amount of  $CO_2$ , and a bigger adsorption column is needed to increase the gas liquid contact surface. Additionally, regeneration is more difficult because this step relies solely on the difference in  $CO_2$  concentration, which is lower at atmospheric pressure [45].

This technique can be implemented on a smaller scale, in a rural environment. In this case the implementation costs can be significantly reduced. However, this leads to higher losses [46].

Water scrubbing is a widely used technique, particularly efficient at large scales, with flow rates exceeding  $500 \text{ Nm}^3/\text{h}$ , however this method is also often used at smaller scale projects that aim to upgrade biogas in an affordable manner. It is an effective method that is easy to control due to the adjustability of water flow and pressure. This process is often accompanied by higher investment but lower operating costs, comparable to those of chemical scrubbing [32], [47], [48].

## Biological removal

The use of biological systems for upgrading biogas is a relatively new and experimental method. This approach utilizes microorganisms or algae to achieve the desired effect and can remove both  $H_2S$  and  $CO_2$  from biogas.

Microorganisms and algae metabolize  $H_2S$  along with water, converting it into sulfate ( $SO_4^{2-}$ ), which serves as a nutrient.  $CO_2$  removal is typically achieved through two main pathways. The first involves adding hydrogen ( $H_2$ ), where hydrogenotrophic bacteria convert  $CO_2$  and  $H_2$  into methane and water. While this method is faster, it requires a constant supply of  $H_2$ . An alternative method uses effective microorganisms (EM), specifically photosynthetic microorganisms, to convert  $CO_2$  and water into  $CH_4$  under the influence of sunlight. Alternatively, algae can be used. The biogas is bubbled through a water layer containing algae to optimize  $CO_2$  absorption and enhance methane production. Furthermore, the algae can be harvested for further applications, such as biofuel production or nutrient recovery [49], [50], [51].

These methods generally have low startup costs but higher operational expenses due to the ongoing need for hydrogen or new effective microorganisms. A significant limitation is the slower and less predictable processing time, which is influenced by factors such as temperature pH and other environmental factors. Due to limited large-scale implementation, there is still little known about the long-term sustainability of this technology [32], [35].

### 2.1.3 Removal of just $CO_2$

## Membrane

Membrane separation operates by passing biogas through a membrane that selectively prevents the passage of  $CH_4$ . This technique can be implemented in two ways: gas-gas or gas-liquid. In both methods, the membranes are sensitive to  $H_2S$  and water, which must be removed from the gas in a preparatory step to prolong the lifespan of the membranes [35]. A principle sketch is given below in Figure 2.3.

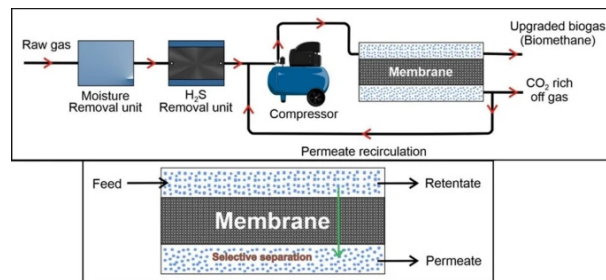


Figure 2.3: Principle sketch of membrane separation [35, p. 4144]

In the gas-gas method, a membrane made of cellulose acetate is typically used. This membrane is particularly effective at separating small polar molecules, such as  $CO_2$ .

Methane concentrations of up to 92% can be achieved. The process can be repeated using a multi-stage membrane system to obtain higher methane purity. The gas must be compressed to a pressure of at least 8 bar. Approximately 10% of the methane remains in the waste gas. However, a variety of membrane materials can be employed in this method. This technique however is seldom used outside of a test setup [52], [53].

An alternative method is gas-liquid membrane separation. In this approach, a liquid flows on one side of the membrane, while the biogas passes on the other side. The liquid contains absorbent substances, such as amines, which facilitate the dissolution of carbon-dioxide in the liquid phase. The absorbent liquid can be regenerated by heating it, releasing the  $CO_2$  in a highly pure form, this can be captured and reused elsewhere, this however falls outside the scope of this project [54].

A significant cost associated with this method is in the pre-treatment phase, where  $H_2S$  should be removed from the gas, although it is not strictly necessary this is recommended to extend the membrane lifespan. Additionally, the membrane needs to be replaced every 5 to 10 years. Maintenance costs are estimated to be about 4% of the initial investment. Overall, the capital and operational costs are relatively low compared to other biogas upgrading techniques. A key disadvantage, however, is the need for a multi-stage system to mitigate these losses. This method is relatively simple to implement and well-suited for small-scale applications with low flow rates [32], [35].

## 2.1.4 Removal of just $H_2O$

### Physical drying method

This method is effective solely for removing water from the gas. The technique is similar to cryogenic separation, but in this approach, the temperature is limited to a maximum of 0.5 °C to prevent ice formation. This temperature is most easily achieved by compressing the gas, then cooling it, and subsequently expanding it to reach a lower temperature. Upon reaching this low temperature, a significant portion of the water vapor condenses into liquid water, which can then be drained off. The resulting gas contains a minimal amount of residual water [32].

The primary drawback of this technique is that it does not remove all the water from the system. To further reduce the water content, the gas must be compressed again and then cooled further. Furthermore, this process requires a lot of energy because of the cooling and compression needed. This process is frequently used as a pretreatment step to increase the efficiency of subsequent processes.

### Moisture trap

In this method, the humid gas is blown through a system. Within this system, the air is directed in such a way that it locally expands causing the temperature and pressure to

drop. As a result, the dew point of the water lowers, leading to the formation of water droplets. These droplets coalesce and can be drained off as liquid water [55].

Alternatively, cyclone separators can be used. In this implementation, in addition to the expansion of the gas, centrifugal force is utilized to more efficiently separate the water droplets [56].

The advantage of this technique is that, in addition to removing moisture, other solid particles, such as dust, can also be eliminated from the gas stream. Furthermore, the technique features a simple design and does not require high investment or operating costs. However, it does not remove all water from the gas, which can pose a problem during the compression step [32].

### **2.1.5 Overview and comparison of available methods**

Table 2.2 provides an overview of the techniques discussed. For each technique, the components removed from the biogas are identified, along with the most relevant advantages and disadvantages of each technique. Out of this table the most optimal method can be selected.

Table 2.2: Upgrading techniques and their advantages and disadvantages [32],[35]

| Method                 | Fractions removed        | Advantages                                                                                | Disadvantages                                                                |
|------------------------|--------------------------|-------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Adsorption             | $CO_2$ , $H_2S$ , $H_2O$ | Low startup cost, able to be deployed for a specific gas fraction.                        | Material needs to be renewed, sensitive to moisture.                         |
| PSA                    | $CO_2$ , $H_2S$ , $H_2O$ | Easy to operate, suitable for small-scale implementation, regeneration possible.          | High capital investment, significant methane losses.                         |
| Absorption             | $CO_2$ , $H_2S$ , $H_2O$ | Efficient solution, able to filter out water and organic material, regeneration possible. | High investment and operational costs, complex to operate.                   |
| Cryogenic separation   | $CO_2$ , $H_2S$ , $H_2O$ | Able to filter out all fraction, easy to transform to liquid bio methane                  | Very energy consuming, expensive investment.                                 |
| Water scrubbing        | $CO_2$ , $H_2S$          | Widely used, highly effective method, easy in operation, regeneration possible.           | Often expensive and better suited for higher scale.                          |
| Biological removal     | $CO_2$ , $H_2S$          | Low startup cost, Enrichment of methane, regeneration possible.                           | High operating costs, difficult to control, very experimental, slow process. |
| Membrane separation    | $CO_2$                   | Simple technique, small operation cost, reliable in small badges.                         | Seldom applied, Complex membrane needed in multiple stages.                  |
| Physical drying method | $H_2O$                   | Simple technique, often used as pretreatment before other techniques.                     | Minimum temperature of 0.5 °C, not all water removed.                        |
| Moisture trap          | $H_2O$                   | Simple technique, often used, cheap.                                                      | Not all water removed.                                                       |

After analyzing the various techniques in Table 2.2, it appears that cryogenic separation and physical drying methods are unsuitable for this project, as they require significant cooling and thus high energy input, which should be minimized. However, if the goal is to further process the gas into liquid methane, these techniques become more suitable.

Biological removal is also unsuitable due to the slow process speed. This method requires careful monitoring to maintain optimal pH and humidity levels and it is a relatively recent technology with limited implementation outside of test setups.

Adsorption, absorption and PSA are not optimal for  $CO_2$  removal on large scales, as these techniques require regeneration due to the absorption or dissolution of gas fractions into the material. The regeneration process is often labor-intensive and time-consuming. Furthermore, the materials involved often need frequent replacement, resulting in high operational costs. However, absorption is suitable for small-scale setups, where sufficient material can guarantee longer times between maintenance requirements and the lower startup cost is more crucial.

Furthermore, adsorption and absorption can be implemented for removing  $H_2O$  or  $H_2S$ , as these components are present in smaller quantities in the gas, lowering operational needs. These methods could serve as pre- or post-treatment stages for another process, or as pre- or post-treatment steps during the gas compression step.

PSA and absorption are both not suitable for this project, as PSA has both a high investment and a high operating cost. Adsorption uses complex chemicals and has slower reaction times.

The two most suitable large scale options are Water Scrubbing and Membrane Separation. Water Scrubbing is effective and widely used, typically on a larger scale, but in some cases, it is also applied on a smaller, more experimental scale. The main drawback is that it often has a higher flow through rate. However, this can be mitigated by working in badges to ensure sufficient gas when the system is operating. Another drawback of Water Scrubbing is its limited effectiveness in removing organic sulfides, a limitation of this method [57].

Membrane Separation can also be a good option due to its simple design and operation. This technique is more commonly used on a small-scale, but it often requires multiple stages to minimize methane loss. This technique sees less small-scale implementations in Africa than water scrubbing, because this technology has a higher methane loss, and because of difficulty to properly maintain the membrane [53]. In this setup, an absorption method is used to remove  $H_2S$  from the gas before the membrane separation.

As this project is working on a small-scale setup, the literature suggests that both absorption and water scrubbing can be suitable techniques. The next section discusses both in greater detail.

### 2.1.6 Different implementations of water scrubbing

Water scrubbing is a widely used process for upgrading biogas. A major advantage of this technique is its ability to process a wide variety of input materials into a more stable output composition [?]. This allows for variation in the system's input without having a significant impact on the output stream.

To ensure optimal performance and extend the operational lifespan of the system, it is crucial to remove  $H_2S$  from the biogas prior to water scrubbing.  $H_2S$  is highly corrosive and can damage components of the scrubbing system, leading to increased maintenance costs and reduced system efficiency. Pre-removal of  $H_2S$  not only protects the system's integrity but also enhances the overall reliability and durability of the process [58].

The water scrubber operates by passing gas and water in opposite directions through an absorption column at a specific pressure. Impurities such as  $CO_2$  and  $NH_3$  dissolve into the water, although a small fraction of methane may also dissolve. The solubility of different components is highly dependent on temperature. Figure 2.4 illustrates Henry's constants for the solubility of various components in water [59].

gasses dissolve in water due to their partial pressures and interactions with water molecules. According to Henry's Law, the amount of gas that dissolves in a liquid is directly propor-



tional to its partial pressure above the liquid [60]. This relationship is quantified by the Henry's Law constant, which varies for different gasses and temperatures. The solubility of gasses in water is influenced by factors such as temperature, pressure, nature of the gas and other gasses present in the fluid. Generally, gasses are more soluble when the water is at a lower temperature. Understanding gas solubility is crucial in fields like environmental science, where it affects the behavior of gasses in natural waters.

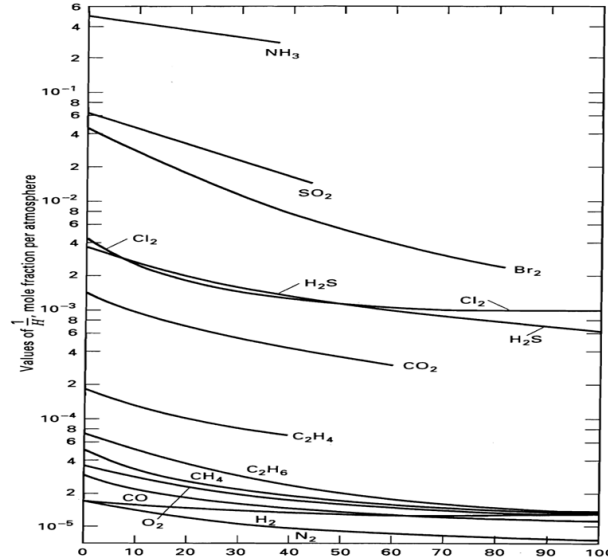


Figure 2.4: Henry's constant in function of temperature for different gasses in water [59, p. 144]

Water scrubbing can be implemented through various configurations, each offering distinct advantages. Figure 2.5 provides a visual representation of several implementations as outlined by [45]. These methods include:

- (A) HPWS with stripping column, without flashing column,
- (B) HPWS with stripping column and flashing column,
- (C) HPWS without stripping column, with flashing column,
- (D) HPWS with degassing pond instead of a stripping column, with flashing column,
- (E) NAPWS with stripping column,
- (F) NAPWS with a degassing pond instead of a stripping column,
- (G) NAPWS without stripping column.

The water scrubbing process can be performed at either high pressure (HPWS) or low pressure (NAPWS). High-pressure operation offers the advantage of increased gas solubility differences, allowing more gas to dissolve and be removed. In contrast, NAPWS requires a higher water flow to achieve the same level of gas removal. Despite this, the overall energy consumption of both techniques is comparable. While HPWS requires less water, it consumes more energy in the compression phase [45]. Since post-scrubbing compression is necessary for gas distribution in this project, HPWS is preferred because it partially pre-compresses the gas. The energy consumption of water scrubbing is inde-

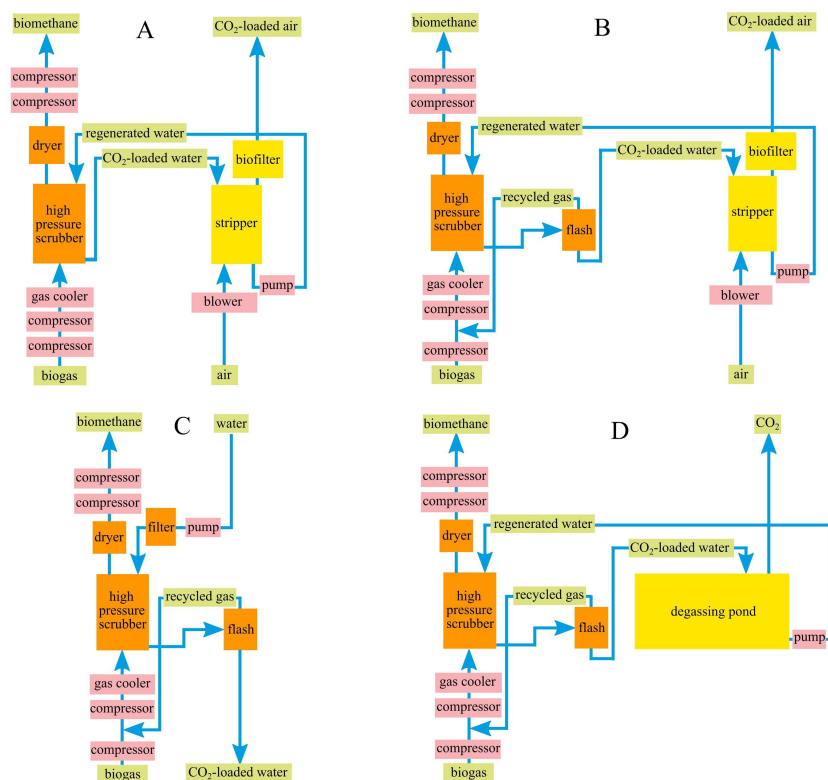


Figure 2.5: Different implementations for water scrubbing [45, p. 5]

pendent of the implementation and ranges between 0.2 and 0.4 kWh/Nm<sup>3</sup> of processed biogas [61].

To ensure continuous operation, the input water for the water scrubbing unit must have a low  $CO_2$  concentration. This is typically achieved by recirculating water employing a stripping or desorption column. Here, the water is expanded to low pressure, reducing its solubility and causing the dissolved gasses to desorb and be released into the atmosphere. These gasses can be captured and further processed if desired [61]. Alternatively, the system can operate with constant fresh water renewal. While this approach maximizes gas solubility, it requires a continuous water supply, making it both energy- and cost-intensive. Another option is using a degassing pond to allow the gas to naturally escape from the liquid over time. However, this also increases operational costs due to the higher water requirements.

When using a desorption column to regenerate the water, alternatively, this column can work using a vacuum. In this case, the gas released is mainly  $CO_2$ , making it easier to capture and further process. However, this falls outside the scope of the current project.

Finally, the inclusion of a flash column in the system significantly reduces methane losses. These losses not only decrease system efficiency but also contribute to greenhouse gas emissions, as methane is a potent greenhouse gas. Minimizing methane losses is therefore crucial for environmental sustainability [62]. For an optimal balance between cost and performance, the use of a single flash column is recommended [63]. This setup achieves a practical compromise, effectively reducing methane losses without incurring excessive costs. Therefore, for this project, a single flash column is the most suitable solution.

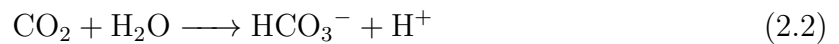
However, for the current project, the inclusion of a flash tank is not ideal due to its higher initial investment costs and increased complexity, which could burden the operation and maintenance of the system in a rural setting. Furthermore, the relatively small-scale of biogas production means that methane losses are less significant, making the cost-benefit ratio of a flash tank less favorable for this specific implementation.

### 2.1.7 Different implementations of absorption scrubbing

Various methods exist for removing  $CO_2$  from gas streams using absorption techniques, each with specific advantages and disadvantages. The choice of absorbent material depends on factors such as efficiency, cost, availability, safety and environmental impact. This section discusses different commonly used absorption materials, with a focus on their applicability in rural areas. The materials are compared on the basis of their chemical reactions, ease of use, and the feasibility of regeneration or alternative applications for their byproducts.

The fundamental principle behind absorption techniques for  $CO_2$  capture is analogous to that of water scrubbing, where the  $CO_2$  gets removed from the gas stream by dissolving in water. The difference between the methods lies in the process used to extract dissolved  $CO_2$  from the water. In water scrubbing, a pressure differential between the absorption and desorption columns drives the extraction, whereas in absorption based techniques,  $CO_2$  is removed from the fluid phase by reacting with the absorbent material.

When  $CO_2$  is introduced into water, it undergoes several reactions with  $H_2O$ . The pH determines which reactions dominate. At high pH levels, the solubility of  $CO_2$  is maximized due to the predominance of reaction (2.1), whereas at neutral pH, the reaction (2.2) dominates [64]. This then requires a further reaction (2.3) before it can react with the absorbent materials. This final reaction is slow and limits the reaction speed [65]. At low pH, although a similar reaction occurs as at neutral conditions, the solubility of  $CO_2$  decreases significantly. Ultimately, the reaction between  $CO_2$  and water leads to the formation of carbonates in the form of  $(CO_3^{2-})$ .



Although many methods exist to remove  $CO_2$  from water, this study focuses on the most accessible options for rural Tanzania. Generally, the most employed substances are calcium hydroxide ( $Ca(OH)_2$ ), calcium oxide ( $CaO$ ), sodium hydroxide ( $NaOH$ ), potassium hydroxide ( $KOH$ ),  $NH_3$  and monoethanolamine ( $MEA$ ) [66], [67].

Calcium hydroxide dissociates in water, and once  $CO_2$  is converted to carbonate ions ( $CO_3^{2-}$ ), it reacts with calcium ions present in the solution to form calcium carbonate

( $CaCO_3$ ) [65]. This precipitate is easily separated from the liquid. Due to its low cost and ready availability,  $Ca(OH)_2$  is well suited for small-scale applications. However, its relatively low solubility in water slows the reaction kinematics and necessitates periodic replenishment or stirring to maintain adequate concentrations [68]. Although regeneration of the precipitated  $CaCO_3$  is technically possible, it requires temperatures up to 765 °C and is therefore not feasible for local applications [67]. Alternatively, the  $CaCO_3$  precipitate can be repurposed in multiple ways, including balancing of soil pH or as an additive in cement [69], [70]. Calcium oxide exhibits properties similar to those of  $Ca(OH)_2$ , but requires a less mass to achieve equivalent removal of  $CO_2$ . Its biggest downside is the higher price than  $Ca(OH)_2$ .

Sodium hydroxide, which dissociates completely in water, reacts with carbonate ions to form sodium carbonate ( $Na_2CO_3$ ). Although the high solubility of  $NaOH$  results in rapid reaction kinetics, the byproduct  $Na_2CO_3$  remains dissolved in the aqueous phase. This continuous dissolution inhibits the reuse of water and eventually causes the reaction to cease, even in the presence of undissolved  $NaOH$ . The high ecological impact of  $NaOH$  and its complex and expensive regeneration make this substance not feasible for this project [64], [71].

$KOH$  exhibits reaction kinetics and solubility similar to those of  $NaOH$  but it is even more costly. However, in contrast to  $NaOH$ , the reaction by-product precipitates and is commonly used as a fertilizer, which provides a potential advantage [72].  $KOH$  and  $NaOH$  also have a significant environmental impact during their production processes [73].

$NH_3$  presents an alternative option. Besides removing  $CO_2$ , it is capable of removing  $H_2S$  from the gas stream. The dissolved ammonium ions ( $NH_4^+$ ) react with  $CO_3^{2-}$  to form ammonium bicarbonate ( $NH_4HCO_3$ ). Due to the high solubility of ammonia, no continuous replacement is needed and the reaction proceeds rapidly. However, the toxic nature of  $NH_3$  requires additional steps to remove any evaporated ammonia from the gas stream, as well as safety challenges during maintenance [74]. The formed  $NH_4HCO_3$  is an excellent fertilizer that enriches soil with nitrates, or can be regenerated by heating the solution to approximately 80 °C to release  $CO_2$  [75], [74]. However, a significant drawback is the relatively high cost of ammonia. Another major drawback of using ammonia is the environmental impact if the gas is able to escape into the atmosphere [76].

Finally,  $MEA$  is widely used as an adsorption agent due to its high absorption capacity and fast reaction kinetics [67].  $MEA$  is often regenerated through thermal desorption or chemical stripping [67]. However, these regeneration processes are not feasible in rural settings.  $MEA$  is typically used in large-scale operations that can make use of regeneration [67]. In these installations, the high material cost is less important due to the regeneration options.

## Overview and comparison

Table 3 provides an overview of these techniques along with their advantages, disadvantages and regeneration or alternative use options.

Table 2.3: Comparison between different  $CO_2$  absorbents

| Material   | Byproduct  | Advantages                                                        | Disadvantages                                                               | Regeneration                                                       |
|------------|------------|-------------------------------------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------|
| $Ca(OH)_2$ | $CaCO_3$   | Safe to handle, easy to acquire, ideal for small-scale.           | Slow reaction, low solubility.                                              | Not feasible, alternative uses as fertilizer or building material. |
| $CaO$      | $CaCO_3$   | Less mass needed than $Ca(OH)_2$ .                                | Similar to $Ca(OH)_2$ , but higher cost.                                    | Similar to $Ca(OH)_2$ .                                            |
| $KOH$      | $K_2CO_3$  | Highly soluble, high efficiency.                                  | Corrosive, high cost, dangerous to handle.                                  | Not feasible, alternative use as fertilizer.                       |
| $NaOH$     | $Na_2CO_3$ | Fast reaction, highly soluble.                                    | Corrosive, dangerous to handle, high eco impact.                            | Feasible when using $Ca(OH)_2$ , byproduct dissolves in water.     |
| $NH_3$     | $NH_4CO_3$ | Fast reaction, highly soluble.                                    | Toxic, $NH_3$ slip into the gas, dangerous to handle, environmental impact. | Thermal regeneration (80 °C), alternative use as fertilizer.       |
| $MEA$      | $MEACOO^-$ | Effective for deep purification, high $CO_2$ absorption capacity. | Suitable mainly for large scale, toxic, hard to acquire.                    | Not feasible, no alternative use, waste.                           |

After comparing these techniques in Table 2.3, it appears that although  $MEA$  is highly efficient, it is unsuitable for this project. This technique is predominantly used on a large scale, where regeneration is feasible and the cost of absorption materials is less critical.

$NH_3$  is not a viable material for this project. In addition to its environmental impact, the gas may escape into the gas stream. Given that this gas is toxic and the installations are located and maintained in rural areas, it does not represent the best option. Because  $NH_3$  is a gas, it has to be transported as an aqueous solution, which drives up the cost.

$NaOH$  and  $KOH$  are good alternatives for an absorption material. However, they are relatively expensive and the  $NaOH$  reaction products remain dissolved in water. This requires frequent water replacement. In addition to that, the environmental impact of the production of these materials is high, consequently, these materials are unsuitable.

$CaO$  and  $Ca(OH)_2$  represent the most promising solutions. They are cost-effective, their reaction products can be reused, and they are safe and readily available. However, their limited solubility requires constant stirring to maintain an adequate concentration of the absorption material, otherwise the efficiency will be inadequate. Of these two options,  $Ca(OH)_2$  is best suited for this project due to its lower cost compared to  $CaO$ .

## 2.2 Compression

Compression is a vital process in the management of biogas, impacting its efficiency and usability. This section examines the key risks associated with compression, such as surge phenomena, dew point considerations, the corrosive effects of hydrogen sulfide  $H_2S$  and the danger of self-combustion. Additionally, it evaluates the types of compressors most suitable for biogas applications, focusing on their performance and operational requirements.

### 2.2.1 Risks associated with compression

When dealing with the compression of biogas, several risks must be considered to ensure the safety and efficiency of the system. Understanding these risks and implementing appropriate solutions is essential for successful operation.

#### Surge phenomena

Surge is a dangerous condition that occurs in centrifugal compressors when the flow rate through the compressor drops below a critical level, causing a reversal of flow and rapid pressure fluctuations. This can lead to severe vibrations, noise, mechanical damage, and reduced compressor efficiency [77].

To counter surge, one of the most common methods is the use of an anti-surge or recycle valve, which redirects part of the compressed gas back to the compressor inlet to maintain flow and avoid low-flow conditions [78].

Ensuring the compressor operates within its designed surge margin and considering fluid properties during system design are key to preventing surge. Lower-density gasses like biogas require more careful surge control, as they are more prone to experiencing surge at lower flow rates [79].

#### Dew point considerations

The biogas leaving the digester is saturated with water vapor, this will lead to condensation during compression. Pre-compression cooling is typically employed to condense a portion of this water vapor, yet a fraction remains in the gas phase, retaining a risk of condensation at various stages within the compression and storage systems. This condensation can introduce significant risks.

Of particular concern is that any  $H_2S$  in the presence of condensed water creates a highly corrosive mixture. This corrosion can severely impact the structural integrity and longevity of metallic components within compressors, pipes and storage tanks [24]. To address these risks, precise dew point management is essential. By utilizing existing experimental data and models, systems can be designed to effectively prevent two-phase formation during the compression process [80].

## Hydrogen sulfide management

During biogas compression,  $H_2S$  poses a significant threat due to its corrosive properties. As the gas is compressed, its concentration increases, which enhances its reactivity with metals commonly used in compressors and gas storage systems. The presence of moisture and elevated temperatures further intensify this corrosion risk, potentially leading to equipment failure. Therefore, it is crucial to implement effective removal techniques for hydrogen sulfide prior to compression to safeguard the integrity of the system and prolong the lifespan of its components [24].

Ensuring the effectiveness of the hydrogen sulfide  $H_2S$  removal system is especially critical during the testing phase. Comprehensive testing must confirm that  $H_2S$  is adequately removed before implementing compression and storage. Failing to do so may result in rapid equipment breakdown.

## Self-combustion

The presence of methane and hydrogen in the biogas mixture introduces a potential risk of combustion. However, due to the low oxygen content in the gas, the risk of self-combustion within the system is negligible [81]. Combustion becomes a concern only if the gas escapes due to equipment failure. Biogas itself has a high self-ignition temperature of approximately 630 °C, meaning that combustion requires significant heat or an ignition source, such as sparks [81]. To mitigate this risk, the system should be equipped with safety measures, including pressure gauges designed to detect leaks. A drop in pressure, indicative of a leak, should be a trigger for the shutdown of the installation, preventing further gas release and ensuring operational safety.

### 2.2.2 Type of compressor

Selecting the appropriate compressor type for biogas applications is crucial for optimizing efficiency, reliability, cost-effectiveness, and the longevity of the system. This comparison will focus exclusively on centrifugal and reciprocating compressors, as other compressors are not cost-effective for the project. Figure 2.6 helps with the choice of compressor type by showing the different operating ranges of various compressors.

As Figure 2.6 shows, the reciprocating compressor can be used at low flow rates and high pressure increases. Centrifugal compressors become more applicable at 1000 m<sup>3</sup>/h or higher. Axial compressors are not relevant here, as such high flow rates will not be reached.

#### Centrifugal compressors

Centrifugal compressors are widely used in applications where high flow rates and moderate pressure increases are required. They operate by accelerating gas through a rotating

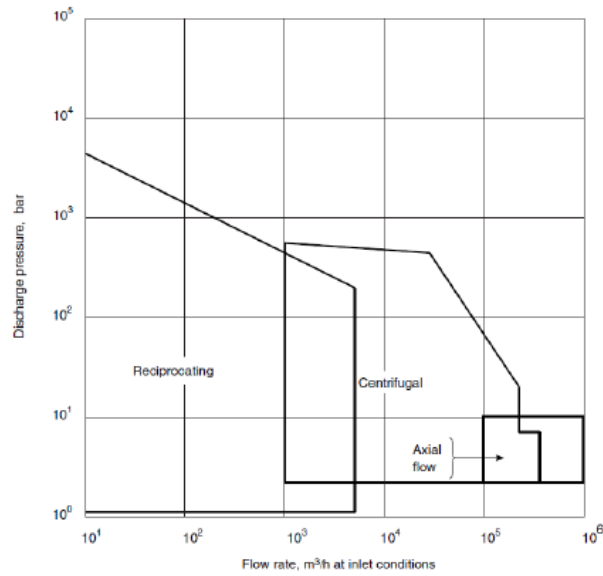


Figure 2.6: Compressor operation ranges [82]

impeller and then decelerating it in a diffuser, converting velocity into pressure.

One limitation of centrifugal compressors is their tendency to experience surge at lower flow rates, which requires careful control mechanisms to prevent this issue. Additionally, their efficiency can decline when the system encounters significant fluctuations in biogas flow. Consequently, if a centrifugal compressor is chosen for a relatively low flow rate project, the implementation of an anti-surge valve will be essential [83], [84].

### Reciprocating compressors

Reciprocating compressors operate by trapping gas in a cylinder and compressing it with a piston. They are particularly well-suited for applications with low flow rates and high pressure requirements, making them an excellent choice for the project, which functions on a smaller scale. These compressors have high efficiency, even when handling variable flow rates, which is advantageous for biogas systems that may not produce gas consistently [83]. In addition, they are typically more cost-effective than other compressor types. However, reciprocating compressors have some drawbacks, including a higher maintenance demand due to their many moving parts and increased noise levels [84], [85].

### Comparison of compressor types

The reciprocating compressor appears to be the most suitable choice, given the lower flow rates and need for higher pressure increases. Although centrifugal compressors offer better performance at larger scales, they are less efficient at the flow rates expected in this project. Thus, selecting a reciprocating compressor would align better with the operational conditions.



## 2.3 Power consumption

This section of the literature review addresses the powering of the biogas upgrading and compression processes. Given the absence of an electrical grid at the site, the project requires a standalone power supply capable of operating independently. Moreover, in alignment with sustainability goals, this power supply should be entirely sustainable.

The following sections will discuss the generation of power for the system, the methods for energy storage, and the integration of solar panels with a battery system.

### 2.3.1 Means of power generation

This chapter explores the principles of power generation for the project. Fossil fuels have been deemed nonviable due to their environmental impact and unsuitability for the project's objectives. As a result, only sustainable solutions such as solar, wind, hydroelectric and biomass (in the form of biogas) remain. However, hydroelectric power is not available at the site and will therefore be excluded from further discussion.

While utilizing biogas from the installation as a fuel source is a potential option, it would reduce the biogas supply available for end users and involve continuous maintenance of a biogas-powered generator. To prioritize maximum energy availability for households and minimize operational complexity, this chapter will instead focus on solar and wind energy and examine the potential benefits of combining these two sources.

#### Solar (photovoltaic)

Solar energy appears to be the most straightforward energy source for the region, due to the consistently high levels of sunlight throughout the year. Figure 2.7 shows solar irradiation in the form of the average direct normal irradiation per year.

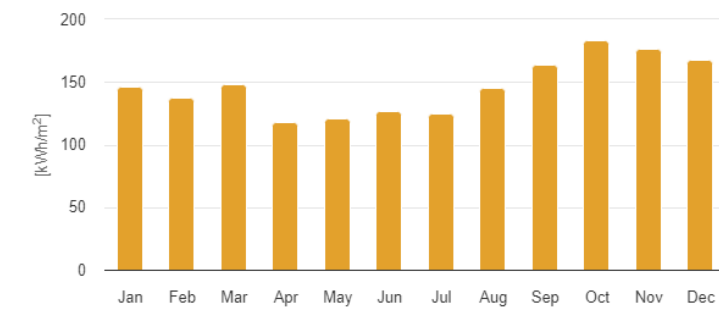


Figure 2.7: Monthly solar irradiation for Kigamboni [86]

As illustrated in Figure 2.7, the region receives significant direct normal irradiation (DNI) on a monthly basis. This data shows that seasonal variations in sunlight are minimal, ensuring a steady supply of solar energy throughout the year. However, when the data is analyzed on an hourly basis, a different pattern emerges. Figure 2.8 illustrates the average solar irradiation available per hour throughout the day on a monthly basis.

A key challenge with solar energy is its intermittency, as sunlight is only available during

|         | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0 - 1   |     |     |     |     |     |     |     |     |     |     |     |     |
| 1 - 2   |     |     |     |     |     |     |     |     |     |     |     |     |
| 2 - 3   |     |     |     |     |     |     |     |     |     |     |     |     |
| 3 - 4   |     |     |     |     |     |     |     |     |     |     |     |     |
| 4 - 5   |     |     |     |     |     |     |     |     |     |     |     |     |
| 5 - 6   |     |     |     |     |     |     |     |     |     |     |     |     |
| 6 - 7   | 9   | 1   |     | 7   | 5   | 2   |     | 4   | 11  | 57  | 82  | 50  |
| 7 - 8   | 156 | 148 | 201 | 204 | 193 | 179 | 154 | 197 | 238 | 314 | 327 | 279 |
| 8 - 9   | 270 | 285 | 349 | 330 | 327 | 329 | 309 | 346 | 366 | 433 | 429 | 373 |
| 9 - 10  | 377 | 413 | 423 | 373 | 374 | 400 | 368 | 408 | 469 | 557 | 529 | 457 |
| 10 - 11 | 456 | 469 | 470 | 413 | 423 | 455 | 430 | 483 | 573 | 616 | 610 | 530 |
| 11 - 12 | 512 | 527 | 502 | 432 | 452 | 488 | 457 | 528 | 624 | 661 | 658 | 581 |
| 12 - 13 | 537 | 562 | 520 | 434 | 442 | 492 | 461 | 540 | 636 | 666 | 667 | 612 |
| 13 - 14 | 553 | 579 | 536 | 422 | 426 | 479 | 456 | 536 | 641 | 678 | 657 | 615 |
| 14 - 15 | 556 | 582 | 546 | 415 | 416 | 455 | 455 | 526 | 627 | 655 | 634 | 613 |
| 15 - 16 | 518 | 537 | 531 | 386 | 370 | 419 | 416 | 480 | 566 | 585 | 569 | 553 |
| 16 - 17 | 430 | 451 | 426 | 322 | 308 | 343 | 340 | 403 | 458 | 467 | 458 | 453 |
| 17 - 18 | 295 | 316 | 260 | 187 | 164 | 178 | 191 | 237 | 250 | 229 | 253 | 273 |
| 18 - 19 | 51  | 48  | 13  |     |     |     |     | 8   | 2   |     | 1   | 13  |
| 19 - 20 |     |     |     |     |     |     |     |     |     |     |     |     |
| 20 - 21 |     |     |     |     |     |     |     |     |     |     |     |     |
| 21 - 22 |     |     |     |     |     |     |     |     |     |     |     |     |
| 22 - 23 |     |     |     |     |     |     |     |     |     |     |     |     |
| 23 - 24 |     |     |     |     |     |     |     |     |     |     |     |     |

Figure 2.8: Hourly DNI [Wh/m<sup>2</sup>] for Kigamboni [86]

daytime hours. Regardless of the season, solar energy can be harnessed in Kigamboni between the hours of 7:00 and 18:00 each day. If continuous operation is desired, energy storage systems are required to ensure nighttime operation.

## Wind

Wind speed is the primary factor in determining the viability of wind energy. In many locations, wind speeds may not be consistently high enough to generate sufficient power [87]. This variability introduces a level of unpredictability in the use of wind energy, particularly at the Kimbiji site where local wind patterns are not well documented. In the general area however, the wind speeds are documented, this is shown at an altitude of 10 m in Figure 2.9.

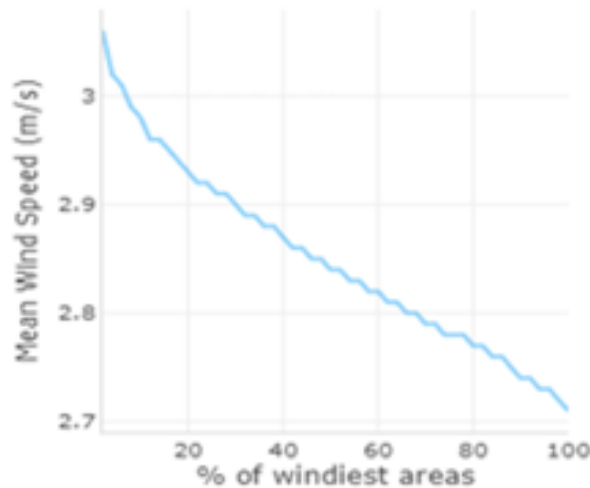


Figure 2.9: Mean wind speed at 10 m altitude [88, p. 1566]

As depicted in Figure 2.9, the maximum mean wind speed at a height of 10 m reaches just over 3 m/s. Since most commercial wind turbines require a minimum cut-in speed of approximately 3 m/s [89], harnessing wind energy at this height is not feasible. To evaluate the potential for wind energy generation at higher altitudes, the wind speed at 50 m is examined, as shown in Figure 2.10.

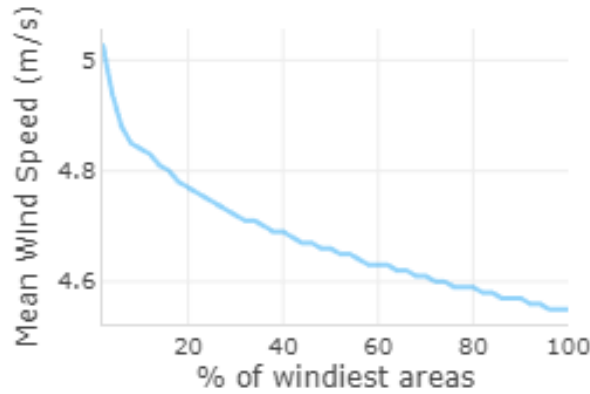


Figure 2.10: Mean wind speed at 50 m altitude [88]

At 50 m, wind speeds are just below 5 m/s. This is sufficient to make wind energy a viable source of power generation [89]. However, this increased viability comes at the cost of higher construction expenses due to the elevated height required for the turbine installation.

### Hybrid solar-wind

Solar and wind energy are widely recognized as two of the most environmentally sustainable energy sources globally. However, both are characterized by variability and intermittency, often rendering them insufficient to meet peak energy demand due to fluctuations in meteorological and climatic conditions [90]. The integration of solar and wind technologies into a hybrid energy system is increasingly considered a viable solution to mitigate these limitations [91]. In such systems, the variability in energy output from one source can be offset by the other, enhancing the reliability of meeting energy demand.

This configuration proves particularly advantageous when continuous operation of the installation is required, as it enhances the system's overall operational reliability.

### Summary of energy generation techniques

In summary, the choice of power generation for the project will depend largely on the operational requirements of the filtration system and packaging. If the filtration process demands a constant, uninterrupted power supply, a hybrid solar-wind energy system would be the most reliable solution. By integrating solar and wind energy, the system would mitigate the variability of either source, ensuring continuous operation and enhancing overall system reliability. However, if the filtration can operate in batches, where power

interruptions are acceptable, the complexity and cost of a hybrid system may not be necessary.

Given the project's budget constraints, solar panels are the most practical solution. The region's consistent sunlight ensures reliable energy generation, and while wind could complement solar, the additional cost of turbine installation at the necessary height makes it expensive and less viable. Therefore, unless constant power is essential, solar energy should be sufficient for the project's needs.

### **2.3.2 Battery types**

In off-grid solar Photovoltaic (PV) systems, a battery plays a crucial role not only for energy storage but also for maintaining system stability. While working in batch production during periods of high energy generation reduces the need for large-scale energy storage, a battery remains essential. It helps regulate voltage and ensures a stable power supply during fluctuations in energy generation and demand. Without proper power management, the voltage could experience inconsistencies that affect both the efficiency and longevity of the equipment. The battery buffers these fluctuations, ensuring a reliable and steady power output to end users.

When selecting a battery type for storing solar energy, several factors must be considered, including efficiency, cost, lifespan, depth of discharge (DoD), and suitability for large-scale or off-grid applications like your biogas installation in Kimbiji. Below is a comprehensive comparison of the most viable battery types for solar energy storage.

#### **Lead-acid batteries**

Lead-acid batteries are available in several types, including Flooded Lead-Acid (FLA), Absorbent Glass Mat (AGM) and Gel batteries. One of the primary advantages of lead-acid batteries is their cost-effectiveness. They are among the most affordable options in the market, making them particularly appealing for projects constrained by budget. Furthermore, lead-acid technology is widely available and well-established, providing a reliable solution for small-scale energy storage applications in rural areas [92].

When comparing the three battery types, FLA, AGM, and Gel batteries, several factors must be considered, including maintenance requirements, performance, lifespan, and overall suitability for the project in Kimbiji. Flooded Lead-Acid batteries are known for their cost-effectiveness and widespread availability. However, they necessitate regular maintenance, which poses a challenge in the remote setting [93, p. 21].

Conversely, Gel and AGM batteries offer a sealed design that prevents spills and reduces maintenance needs. Gel batteries typically require precise charging using a controller to ensure they are charged correctly [94]. AGM batteries have a shorter lifecycle than Gel batteries, especially at high temperatures [95]. In order to mitigate the effect of elevated temperatures on battery performance, the implementation of heating, ventilation, and air conditioning systems (HVAC) can be considered, as they help regulate temperature

and thus prolong battery life. However, this introduces additional costs and logistical complexity, as HVAC systems require their own maintenance. Despite this, HVAC maintenance expertise is generally available, even in remote rural areas, making it a feasible option [96].

In evaluating the lead-acid battery options, it becomes evident that each type offers distinct advantages and challenges. Due to their widespread availability in rural areas, Flooded Lead-Acid batteries may be more accessible and, therefore, potentially more suitable for the project in Kimbiji. Nonetheless, the final selection will ultimately depend on local availability and the other choices made within the system.

### **Lithium-ion batteries**

Lithium-ion ( $\text{LiFePO}_4$ ) batteries present a highly viable alternative for energy storage solutions, particularly if long-term reliability is required [97]. In addition to their extended lifespan and high efficiency, lithium-ion batteries require little to no maintenance, making them especially suitable for remote or off-grid applications where regular maintenance might be challenging [98]. Another key advantage of  $\text{LiFePO}_4$  batteries is their enhanced resistance to temperature fluctuations, which is critical for installations in environments with extreme or variable climate conditions like those in Kimbiji [99]. Furthermore, lithium-ion batteries have a lower ecological footprint compared to lead-acid alternatives [100].

Other types of lithium batteries, such as lithium cobalt oxide ( $\text{LiCoO}_2$ ), lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA), are not relevant for this project due to their higher costs and complex safety requirements. These typically prioritize high energy density and fast charge or discharge cycles, which are less critical in small-scale, off-grid solar energy storage systems [101], [102].

However, it is important to consider that lithium-ion batteries generally come with a higher initial cost compared to lead-acid alternatives [92]. Despite this, their prolonged lifespan and superior energy efficiency may offset the higher upfront investment.

### **Overview of battery technologies**

In summary, the choice between lithium batteries and lead-acid batteries for the Kimbiji project depends on several key factors. Lithium Iron Phosphate ( $\text{LiFePO}_4$ ) batteries require a higher initial investment but offer superior longevity and efficiency, making them a better option in the long run for off-grid applications. In contrast, lead-acid batteries, including Flooded Lead-Acid (FLA), Absorbent Glass Mat (AGM), and Gel types, are more accessible and cost-effective, especially given their widespread availability in rural areas.

Ultimately, the decision will be guided by the local availability and budget. If resources permit, investing in lithium batteries is advisable due to their long-term benefits. However, if budget constraints are significant, lead-acid batteries may be the only available

option for the project. However, lead-acid batteries will still meet the operational needs effectively.

### **2.3.3 Charging protocol**

In the context of small-scale solar energy storage, choosing the appropriate charging controller is essential for maximizing battery performance. Two widely used methods are Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT).

#### **PWM**

Pulse width modulation controllers are simpler and more cost-effective, making them suitable for budget-constrained projects like this. PWM works by gradually reducing the current as the battery approaches full charge, which helps to prevent overcharging. However, PWM is less efficient, particularly in systems with higher voltage solar panels or in variable weather conditions, as it cannot optimize the energy harvested from the solar array [103], [104].

#### **MPPT**

Maximum Power Point Tracking controllers are more advanced and efficient, as they continuously adjust the voltage to maximize the power output from the solar panels. MPPT is particularly effective in environments with fluctuating sunlight, which would be beneficial in the project to ensure the maximum amount of energy is harvested from the solar panels. Despite being more expensive than PWM, the higher energy yield and improved battery charging efficiency offered by MPPT can justify the initial cost for long-term reliability and performance [103], [104].

For budget-conscious projects, a cost-effective alternative to commercial MPPT systems is to implement a custom-built solution using platforms like Arduino. This approach has been shown to achieve satisfactory results in similar applications [105], [106], offering the advantages of MPPT without the high expense typically associated with the commercial systems.

### **Comparison of charging protocols**

Given the project's tight budget, PWM charging emerges as the more suitable option. PWM is a simpler and reasonably efficient charging protocol, aligning well with the financial constraints of the project. However, if possible, the custom-built MPPT approach could provide a valuable alternative that does not significantly increase costs but improves efficiency.

## 2.4 Operation and distribution

In this section, the study examines the operation of biogas plants and the distribution of biogas. A critical first step is to understand the profile and needs of the biogas users. By gaining insight into user behavior and patterns of biogas consumption, it becomes possible to optimize the functionality of the system. Additionally, this analysis will address common operational challenges faced by biogas plants, including technical issues, maintenance practices, and the overall sustainability of the system. These must be taken into account as they significantly affect the long-term performance and reliability of biogas systems.

### 2.4.1 User profile

The project is located in Kimbiji, approximately 34 km from Dar es Salaam, the largest city in Tanzania. To optimize the impact of the project, the biogas produced should be efficiently distributed to the local population, ensuring equitable access and maximizing the benefits for the community, rather than being transported and used elsewhere.

Biogas can be utilized for a variety of purposes. Both biogas and biomethane can serve as vehicle fuel, but this requires specialized systems, which are often lacking in rural Africa. Biogas can also be converted into electricity using a generator, providing a potential energy source. However, this solution is often impractical in areas without an established electrical grid to which the system can be connected. In such communities, biogas is primarily used for lighting, cooking, or a combination of both, as this solution is easy and inexpensive to implement [107].

In a household, energy consumption for cooking is the largest contributor to overall energy use. Although biogas can also be used for lighting, it requires significantly less energy compared to cooking. In the current situation, an average household uses 2.2 kg of firewood for cooking, which corresponds to an energy value of 9.9 kWh [108]. This amount of energy is equivalent to approximately 1.6 Nm<sup>3</sup> of unfiltered biogas [4]. When the gas is upgraded, this volume decreases.

In addition to availability, the price of biogas is a crucial factor in determining the profitability of the system. Currently, firewood and charcoal are primarily used as energy sources. Charcoal is often cheaper than alternatives such as LPG, kerosene, or diesel. However, the price of charcoal is highly dependent on location, especially now that the government has banned the use of charcoal [9]. Another factor that significantly influences its price is the cost of alternative fuels, causing considerable fluctuations. Biogas could become a competitive energy source for the local population, but its price must be lower than that of charcoal to achieve this [109], [110].

An important final factor to consider is the literacy rate of biogas users and adopters. In Tanzania, approximately 20% of the population is illiterate, with rates likely even higher in rural areas [111]. This poses a significant challenge when implementing biogas systems, as they must be designed for ease of use without relying on the ability to read. Ensuring that the system can be operated intuitively and that instructions are accessible to low-literacy users is critical for the successful adoption and long-term functionality of biogas

plants in these communities.

## 2.4.2 Distribution options

To distribute the gas to the local population, two primary methods are generally available: through a small-scale gas network or via a gas holder. Distribution via a gas network is only feasible if the gas is sufficiently compressed and the methane concentration is adequately high. This approach requires significant capital investment, extensive coordination with local authorities, and ongoing maintenance during operation. Additionally, leakage losses are generally higher compared to the use of a gas holder [112].

A more suitable solution involves utilizing a gas holder and transporting it to the desired location. Unlike liquefied petroleum gas (LPG), biogas cannot be easily converted to liquid form. This would only be possible if the biogas were cooled to temperatures below  $-161\text{ }^{\circ}\text{C}$  [113], this is not feasible in this context. The capacity of the gasholder is highly dependent on final pressure, the higher the pressure, the smaller the tank needs to be. The gas tank should be able to hold approximately  $1.1\text{ Nm}^3$  of upgraded biogas per day of cooking [4]. The typical LPG container can carry up to 33 L of gas. LPG typically exerts an 8 bar pressure. However the design allows for gasses upto 25 bar inside of the container [114].

One significant advantage of biogas over alternative energy sources is its potential for local production. In contrast, fuels such as firewood, kerosene, and LPG often necessitate considerable travel for procurement, leading to increased transportation costs and environmental impacts. Furthermore, utilizing a local fuel source like biogas minimizes the environmental footprint associated with fuel transportation, reducing greenhouse gas emissions further [115].

## 2.4.3 Operational problems

In rural Africa, a significant proportion of biogas installations are non-operational. Approximately 50% of the installations in Africa fall into this category. In other parts of the world, the rate of non-operational biogas systems is even higher, with some studies suggesting that in certain Asian countries, only 3% of all installations are fully operational without issues [116]. Figure 2.11 illustrates the most common problems associated with biogas installations.



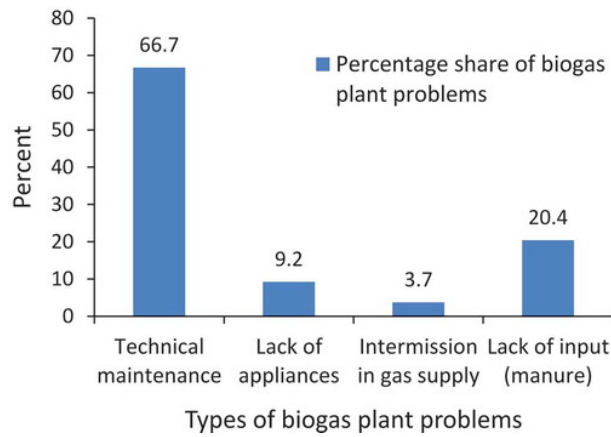


Figure 2.11: Frequency of problems at biogas plants [116, p. 15]

Figure 2.11 indicates that the primary challenge in the implementation of biogas systems is technical maintenance. Once a biogas plant becomes operational, it requires regular maintenance to function effectively. However, this maintenance is often neglected, leading to the gradual degradation of the plant's performance until its output becomes insufficient, eventually resulting in system failure. A second issue related to technical maintenance is the lack of availability of spare parts, which further impairs the proper functioning of the plant. Finally, the technical skills of the operators are often inadequate to properly run and maintain the system [116].

In 10% of cases, the plant ceases operation due to a lack of appliances. This means that either the surrounding area or the plant itself lacks the necessary equipment to utilize the produced biogas, such as lamps, stoves, gas hoses, and related components.

## 2.5 Conclusion

This chapter focuses on a biogas upgrading, compressing and distribution. The biogas primarily consists of methane and carbon dioxide, with smaller amounts of other gasses like  $H_2S$  and  $H_2O$ . To improve its calorific value, the biogas must undergo upgrading to increase methane concentration to at least 70% and reduce harmful components like  $H_2S$ . The upgraded biogas will then be compressed for efficient transport and distribution, with a target pressure of 8–10 bar. As Kimbiji lacks grid power, renewable energy sources will be utilized to drive these processes. The literature review explored methods for upgrading, compressing, and distributing biogas, focusing on efficiency, cost-effectiveness, feasibility, and community impact.

Various techniques for upgrading biogas have been analyzed and water scrubbing emerges as the most promising method for applications within this project. Water scrubbing offers a practical solution because it can be implemented at relatively low cost while maintaining lower operational expenses compared to alternative methods. In addition, the simplicity to operate and the regenerable water contribute to its cost-effectiveness on both small and large scales, making it suitable for diverse setups.

For pre- and post-treatment specifically, adsorption is a highly efficient technique, effectively removing specific gas fractions like  $H_2S$  or moisture. This precision enables ad-

sorption to function as a complementary process in biogas upgrading, enhancing overall gas quality and reducing wear on the water scrubbing unit. Adsorption can also mitigate risks of corrosion in the compressor and toxicity associated with hydrogen sulfide, thereby extending the lifespan of equipment and improving the safety and reliability of the system. However, this technique requires limited maintenance in the form of regeneration, to ensure the adsorption materials can continue working.

The reciprocating compressor is the most suitable choice, given the lower flow rates and the higher pressure increases. Although centrifugal compressors offer better performance at larger scales, they are less efficient at the flow rates expected in this project due to surge. Thus, selecting a reciprocating compressor would align better with the operational conditions.

Effective management of dew point and  $H_2S$  is essential in the compression and storage of biogas to ensure system reliability and longevity. Dew point management mitigates condensation risks, reducing corrosive damage from water and  $H_2S$  interactions. Furthermore, hydrogen sulfide removal prior to compression is crucial to prevent severe corrosion and compressor degradation. Properly addressing these factors enhances the stability and operational efficiency of the biogas compression system.

Powering the biogas upgrading and compression processes will require a standalone, sustainable power supply. Given the project's budget and operational constraints, a solar power system with battery storage presents the most practical and cost-effective solution. Solar energy is highly reliable in this region due to the consistent sunlight. Wind energy could complement it, but the high costs associated with wind turbine installation make it less viable for this project.

Battery selection is crucial to ensure stability and longevity in the off-grid system.  $LiFePO_4$  batteries offer superior efficiency and durability but require a higher initial investment. Lead-acid batteries, on the other hand, are more affordable and widely available in rural areas, although they have higher maintenance needs and shorter lifespan. Given budget constraints, lead-acid batteries may be the only feasible option, though lithium batteries are preferred if funding allows.

The charging protocol choice between PWM and MPPT controllers depends on cost and efficiency requirements. While MPPT is more efficient, PWM controllers offer a suitable budget-friendly alternative. Should time allow for a low-cost, custom-made MPPT solution, this could enhance energy harvesting without excessive costs.

The biogas production aims to meet local needs, providing energy mainly for cooking and lighting, as specialized systems for vehicle fuel or electricity are impractical in rural settings. Households consume about 2.2 kg of firewood daily, equating to 9.9 kWh of energy, which biogas can replace effectively if priced competitively with charcoal, the current dominant fuel source. Additionally, high illiteracy rates, especially in rural areas, mean biogas systems must be designed for intuitive use to ensure successful adoption and long-term functionality in the community.

To distribute gas locally, two primary methods exist: a compressed gas network, which demands high methane concentration and major investment, or a transportable gas holder,

which is more feasible given biogas limitations. Unlike LPG, biogas cannot be easily liquefied, making high-pressure storage essential for efficiency.

In rural Africa, approximately 50% of biogas installations are non-operational due to neglected maintenance, lack of spare parts, and insufficient appliances. Therefore, regular maintenance and the availability of equipment will be essential considerations in the design

# Chapter 3

## Design

Building on the literature review, which examined the theoretical foundations and technological advancements in biogas upgrading, compression, and distribution, this chapter presents a detailed design of the proposed system. The goal is to develop a scalable and efficient biogas processing system tailored to the energy needs and available resources of rural communities, particularly in Kimbiji.

The design phase incorporates insights from prior research while addressing practical constraints such as resource availability, cost-effectiveness, scalability and environmental sustainability. The system is designed for the Kimbiji setup and expected to process approximately 100 L of biogas per day. The design also considers future expansions in Kimbiji, with the potential for expanded biogas production of up to 6,500 L per day. Because both adsorption and water scrubbing seem promising, two main designs will be developed and compared at the university and, if needed, additional designs can be developed and tested. The most optimal design will then be translated into the Kimbiji setup. The selected system can run for a number of hours daily, depending on the amount of biogas generated and the availability of sunlight. The selection of components, considerations for energy supply and structural configurations are all specifically adapted to the climate, resource availability, and technical constraints of Kimbiji. Reliability, functionality and ease of use serve as central principles of the design.

This chapter begins by presenting the proposed concepts, detailing the required components such as the water scrubbing unit, the absorption unit and the energy supply for each concept. The subsequent sections provide detailed dimensioning of the system components. By the end of this chapter, the two main possible designs and their various implementations will be outlined. This will serve as the foundation for the implementation and testing at the university in Chapter 4.

### 3.1 Proposed concept

The design is divided into three parts. The first part focuses on purification and compression using water scrubbing as the central principle. The second part will consider absorption as the main principle. The third part of the design concerns the energy supply, needed to supply the two designs with electricity. Since electricity is available at the

university, this part will not be implemented there but will be installed in Kimbiji.

### 3.1.1 Water scrubbing concept

The proposed water scrubbing design is illustrated in the flowchart presented in Figure 3.1. Central to the design is a water scrubbing column, which removes a significant portion of  $CO_2$  from the raw biogas. Additional components are incorporated to remove  $H_2S$  and moisture. The system is designed to compress the biogas to a final pressure of approximately 8 bar, allowing for efficient storage and distribution.

The primary input for the system is unfiltered biogas, coming directly from the anaerobic digester. In addition to this, ambient air serves as a secondary input stream to facilitate the desorption process within the water scrubbing unit. The system produces two main output streams: a methane-rich biogas, suitable for energy applications, and a  $CO_2$ -rich off-gas, which is vented into the atmosphere. The project expects to deliver about 7.5 L of compressed biogas daily at an 8 bar pressure.

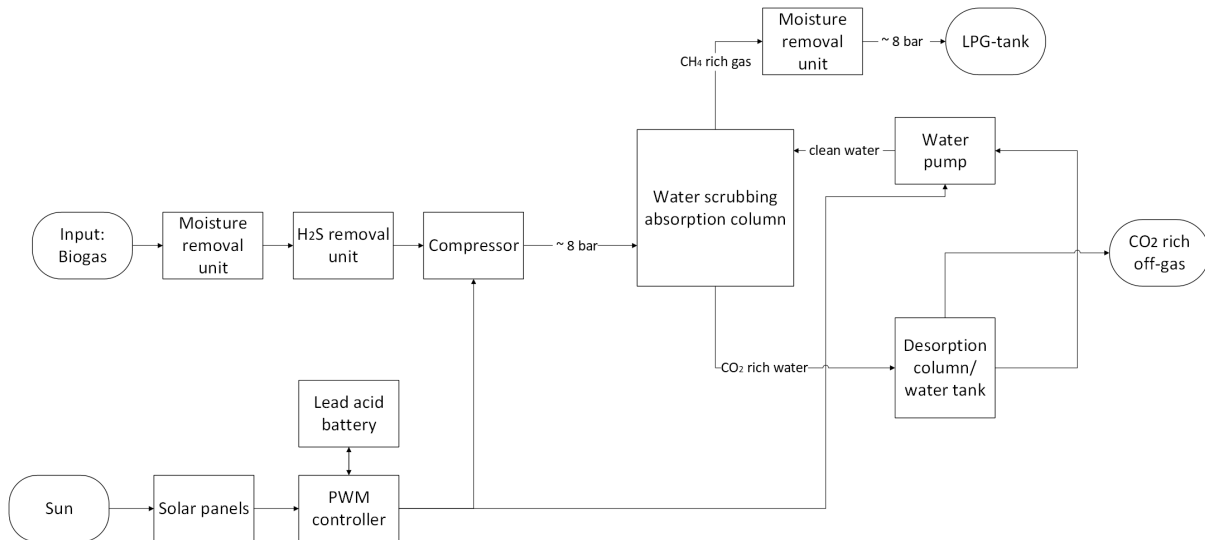


Figure 3.1: Proposed water scrubbing process flowchart

The biogas purification process begins with two preparatory steps, namely the removal of moisture and  $H_2S$  to protect downstream components, particularly the compressor, from excessive wear. The trap facilitates condensation as water droplets form. These droplets coalesce into liquid water that can subsequently be extracted.  $H_2S$  is eliminated through an adsorption process [44].

As the final step in the preprocessing stage, the biogas is compressed to at least 8 bar to facilitate an efficient water scrubbing process. Additionally, having a higher pressure means that a smaller volume is needed to transport the gas, thereby increasing its usability.

Following compression, the gas is directed into the water scrubbing unit for  $CO_2$  removal. In this unit, water flows countercurrent to the biogas stream to enhance the absorption of  $CO_2$  into the liquid phase. When the gas is introduced into the column, the resulting bubbles should be minimized in size to maximize gas-liquid contact. Additionally, trace amounts of  $H_2S$  and  $NH_3$  are absorbed by the water.

The water level in the column is a variable. In the water phase, gas bubbles maximize the interfacial surface area between the gas and the liquid, while in the gas phase, water droplets perform a similar function. After passing through this system, the  $CO_2$  concentration in the biogas is significantly reduced.

The purified gas then passes through a pressure relief valve. This valve ensures a sufficiently high pressure in the water scrubbing column while the storage tank is at a lower pressure. Alternately, this valve can be left out. In this scenario pressure rises through the scrubber as the LPG tank is getting filled, this would simplify the system at the expense of purification efficiency in the beginning of the filling stage. This also requires a higher water flow rate.

In subsequent stages, post processing is employed to remove residual water vapor from the biogas. The gas first passes through an additional moisture trap. Similar to the first moisture trap, this unit can lower the dew point of the water to a minimum of  $5^\circ\text{C}$  [32].

Once adequately dried, the upgraded biogas is stored in detachable LPG tanks for distribution. The size of the portable LPG tanks should be chosen based on how much gas is needed for cooking, the affordability for the locals, and the daily biogas production.

The scrubbing water is regenerated using desorption. In this step, the water is expanded to a lower pressure and exposed to air, allowing the dissolved  $CO_2$  to be released into the atmosphere. How this process works is elaborated in the literature study. The process occurs in a desorption column, which operates at atmospheric pressure.

A water pump pressurizes and pumps the water from this desorption column to the top of the water scrubber. To ensure sufficient water during the process, the desorption column also serves as a water reservoir.

If the system is required to run for multiple days without being able to replace the LPG tank and the throughput exceeds the capacity of an LPG tank, a buffer tank can be incorporated to maintain continuous operation.

### 3.1.2 Adsorption concept

The flowchart in Figure 3.2 illustrates the proposed adsorption design. The central element of this concept is the adsorption column, which removes a significant portion of  $CO_2$  from the raw biogas using an adsorption process. In this design,  $Ca(OH)_2$  is transformed into  $CaCO_3$  to remove  $CO_2$ . Additional components are incorporated to remove  $H_2S$  and residual moisture. The system is designed to compress the upgraded biogas to a final pressure of approximately 8 bar, allowing for efficient storage and distribution.

Like the water scrubbing setup, the primary input for the system is the unfiltered biogas coming from the anaerobic digester. As an additional input, this concept requires a steady stream of  $Ca(OH)_2$ . The system will produce a waste stream in the form of  $CaCO_3$ , which will need to be removed from the column. The useful output will be a methane-rich biogas at 8 bar. The project expects to deliver about 7.5 L of compressed biogas daily at an 8 bar pressure.

The preprocessing and compression stages are equal to those of the water scrubbing

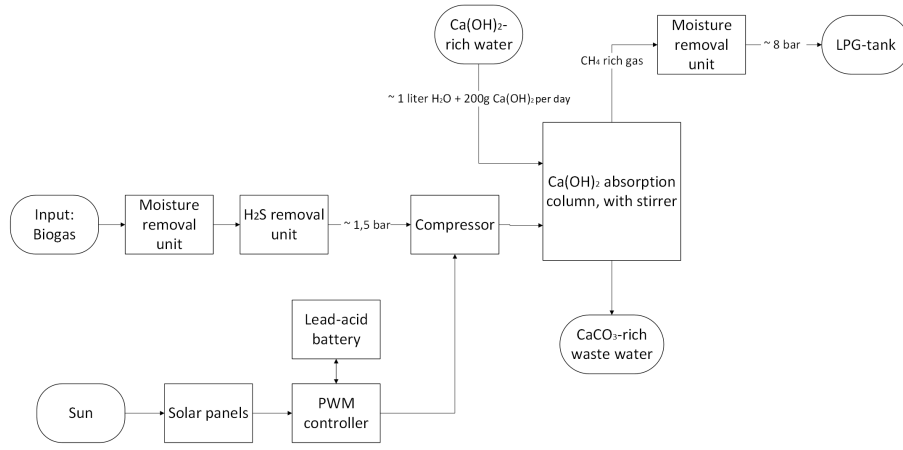


Figure 3.2: Proposed adsorption process flowchart

design. After extracting biogas from the digester, it passes through a moisture trap and an  $H_2S$  adsorption unit. After these stages, the compressor compresses the gas to an 8 bar pressure.

After exiting the compressor, the gas enters the adsorption column, which is filled with water with dissolved  $Ca(OH)_2$ . This material is present in excess to ensure a consistently high concentration of dissolved  $Ca(OH)_2$  throughout the process. To ensure the  $Ca(OH)_2$  stays dissolved, sufficient turbulence in the water is crucial. This can be achieved by directing the gas stream in a way that generates turbulence at the bottom of the column. If this proves insufficient, a stirrer will be required. Similarly to water scrubbing, it is essential that the gas bubbles remain small to maximize fluid-gas contact. The adsorption material can be replaced continuously or on a batch basis. Continuous replacement is more expensive and requires more components, while batch-based replacement requires periodic manual maintenance.

Between the column and the LPG tank there is a moisture removal unit to lower the moisture content in the gas stream. During the process, the pressure in the system gradually builds up. When a new low-pressure LPG tank is attached, the pressure will drop and then slowly increase again as the process continues. The process should be stopped once the digester is empty or the LPG tank is at its final pressure.

The size of the LPG tank can be chosen similar to the water scrubbing concept, depending on the gas needed for cooking, affordability and daily production. Similar to the water scrubbing concept, a buffer tank can be included for ease of use.

## Recirculation

The first absorption concept has two significant shortcomings. The first one is the low removal efficiency of  $CO_2$  compared to water scrubbing. The second is the need for all components of the system to withstand relatively high pressures. These shortcomings can be avoided using gas recirculation. Figure 3.3 illustrates the flowchart of the proposed concept.

The proposed design recirculates the gas, continuously pumping it through the adsorption tank. Secondly, a buffer tank is incorporated into the circuit. This buffer tank stores gas at a lower pressure, thereby reducing stress on the system components. If biogas needs

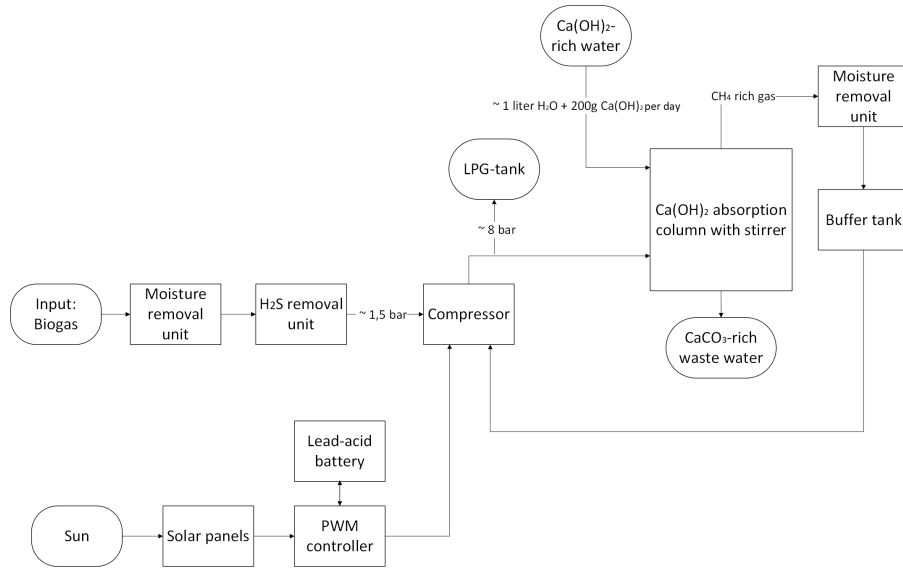


Figure 3.3: Proposed adsorption process with recirculation flowchart

to be extracted from the system, the compressor can draw the gas from the buffer tank and pressurize it to fill the LPG container.

This approach has a slightly higher investment cost than the proposed adsorption without recirculation, but this can benefit the overall performance of the system. Due to recirculation, this setup has longer processing times. In addition, the larger the amount of gas stored in the system, the more biogas can be lost during maintenance.

### 3.1.3 Energy supply

As shown in Figures 3.1, 3.2 and 3.3, the system is powered by solar panels and lead-acid batteries connected to a PWM controller. The complete electrical concept is shown in 3.4.

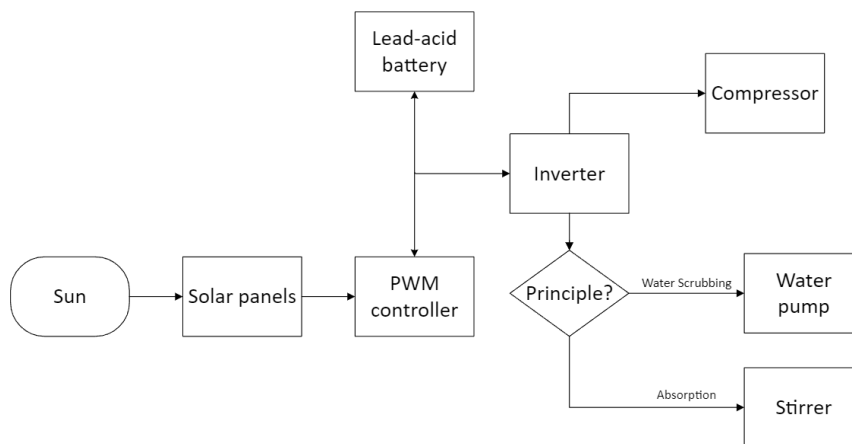


Figure 3.4: Proposed energy flowchart

The solar panels will be sized to provide sufficient power to meet the full load during days with average solar irradiation. The battery pack is designed to sustain operation on moderately cloudy days, though the system will not function during dark days nor



at night, this would make the battery pack economically viable. This solar system will be operated using a PWM controller rather than a MPPT controller, as the cost of the project should be minimized.

The system will supply power to a compressor and, depending on the chosen configuration, either a water pump or possibly a stirrer. These components primarily require a 220 VAC power supply, with the stirrer being the exception, as some models necessitate a DC power supply. An inverter will be used to convert the DC battery voltage to the 220 VAC required by the motors. Although certain components, such as the stirrer or compressor, could theoretically operate on DC, this will be avoided due to safety concerns and the risk of overvoltage or undervoltage conditions. Directly connecting motors to the battery pack exposes them to voltage fluctuations during charge and discharge cycles, which can lead to inefficient operation, overheating, or premature failure. A DC voltage stabilizer can solve this issue, however, these converters are more expensive and harder to source locally compared to widely available inverters.

The battery and the inverter will be housed in a ventilated and shaded enclosure to prevent thermal degradation at high ambient temperatures. The design should be specified with a safety margin to accommodate the cold-start currents of the compressor without overloading the system.

## 3.2 Preprocessing

Before the biogas enters the main upgrading column, it must be conditioned to remove impurities and brought up to the required pressure. The preprocessing stage comprises three successive modules.

The first module is the moisture removal unit. This unit strips out liquid water by expanding and condensing the water vapor. This process prevents corrosion and flooding in downstream components. Secondly, the  $H_2S$  removal unit reduces toxic, corrosive hydrogen sulfide to below 5 ppm, which is the required safety standard for gas. This is achieved using locally available adsorbents, safeguarding the project's longevity.

Finally, the compressor must raise the biogas pressure to approximately 8 bar before the gas enters the water scrubbing or absorption column. This component drives the gas through the subsequent water-scrubbing or adsorption columns.

Each module is sized to handle one week worth of raw biogas production at ambient conditions. Energy consumers should be avoided where possible, and the energy use of these should be minimized. Maintenance should be no more than weekly, assuming a daily biogas flow of 100 L. All parts should be available locally.

### 3.2.1 Moisture removal unit

The moisture removal unit serves as the first step in the preprocessing of biogas after it exits the digester. Its primary purpose is to reduce the humidity content of the raw biogas, thereby protecting downstream components, particularly the compressor, from

water-induced damage or corrosion. Effective moisture removal enhances the efficiency and longevity of the system.

In the proposed setup, moisture is initially extracted by condensation in a moisture trap. The biogas is passed through a trap where pressure conditions favor the formation of water droplets. These droplets coalesce into liquid water, which can be drained from the bottom of the unit. This method is based on the expansion of gas leading to localized cooling and pressure drops, thereby lowering the dew point of water and triggering condensation.

This method of physical drying has, at best, the capacity to lower the dew point to 5 °C [32]. If the biogas enters the system fully saturated at 30 °C, in this scenario, the condensation is 23.6 g/m<sup>3</sup> [117]. Given a weekly amount of biogas of 700 L, the total liquid formed will be 16.5 ml. While minimal, this volume sets the lower bound for the required condensate collection capacity.

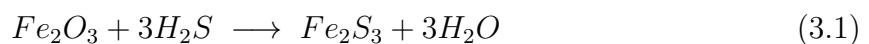
### 3.2.2 $H_2S$ removal unit

Raw biogas typically contains  $H_2S$  in concentrations ranging from 20 ppm to 20,000 ppm [4]. To meet the safety and natural gas quality standards, the residual  $H_2S$  concentration must be reduced to below 5 ppm.

The unit will be designed on the worst-case scenario of  $H_2S$  concentration of 20,000 ppm or 2%. 2% equals approximately 28.35 g/m<sup>3</sup> of  $H_2S$  in the raw biogas, assuming 25 °C at 1 atm and using the Ideal Gas Law. For this setup, this equals 19.8 g of  $H_2S$  that should be removed per week.

This  $H_2S$  will be removed using an absorbent. This project will consider four possible absorbent materials. After testing, the most suitable solution will be determined. These materials were selected because of their local availability.

Granular iron oxide ( $Fe_2O_3$ ) removes  $H_2S$  by chemisorption, forming iron sulfide (3.1). Different types of  $Fe_2O_3$  exist, these include raw, impregnated, and pure  $Fe_2O_3$ . This study will only consider impregnated  $Fe_2O_3$  as it commercially available. This material can be regenerated, however, during regeneration, the material can reach high temperatures and has an explosion risk [32]. Given the rural, uncontrolled conditions, the material should be disposed of properly. Commercially available media can remove up to 560 g $H_2S$ /kg before being exhausted [118], or approximately 35.4 g of iron oxide is required each week.



Steel wool is inexpensive and readily available in local markets. The spent media, however, must be disposed of properly. Although regeneration is possible, this reaction is exothermic and heat build-up can occur in large beds.

Rusted steel wool functions similarly to steel wool: the thin iron fibers offer a high surface area for  $H_2S$  to oxidize into iron sulfides (3.2). The capacity per mass is 10–20 g $H_2S$ /kg of steel wool [118]. This means that 1 kg of steel wool is required each week, assuming the

worst conditions. This is higher than iron oxide, but its low cost and availability make it suitable for this project. The material can be regenerated on-site by exposing it to air.



Finally, a third option is activated carbon. This material is often produced from coconut shells, peat, wood, or coal [119]. The coconut shells are especially interesting as they are a local waste product and could thus be reused within the community.

Activated carbon, often impregnated with alkaline or metal-oxide promoters, removes  $H_2S$  by both physical adsorption and chemical reactions [119]. These reactions depend on the chemical composition of the gas. Typical impregnated carbons can capture up to 100 g $H_2S$ /kg of media before breakthrough [120]. This means that one week of biogas production would require up to 200 g of activated carbon. Its high surface area and microporosity enable rapid uptake. Regeneration is not feasible in this context, as it requires high temperatures and, after regeneration, only achieves low regeneration efficiencies [121]. Additionally, the upfront cost of activated carbon is higher than that of other options, which is impractical for this project.

Each option will be compared in terms of removal efficiency, footprint, capital and operating costs, ease of maintenance, and local availability of materials. The final selection will balance reliability and simplicity, key criteria for off-grid rural deployment.

### 3.2.3 Compressor

As previously discussed, the water scrubbing process requires an operating pressure of approximately 8 bar. The gas flow rate is also critical, as the absorption and water scrubbing efficiencies are dependent on the flow rate.

Selecting an appropriate compressor is essential for the project to succeed. Since the system will handle relatively small daily gas volumes, the compressor does not need to support high flow rates. Instead, the selection should prioritize the ability to achieve high discharge pressures, at least 8 bar, with minimal maintenance requirements.

Furthermore, it is important to consider the compatibility of the compressor with biogas. Biogas contains  $H_2S$  and water vapor, which could lead to corrosion or mechanical wear over time. Therefore, the resistance of the compressor to these chemicals is a crucial factor for maintaining efficiency. The efficiency of the gas pre-treatment step will also be critical to extending the compressor's operational lifetime.

Energy consumption is another relevant factor. The compressor will possibly be the largest energy consumer during operation. Consequently, an energy-efficient compressor should be selected to minimize energy costs.

## 3.3 Water scrubbing setup

To process the biogas, two options were proposed. This section discusses the required dimensions of the most critical components of the water scrubbing setup. This system

consists of three main components: an absorption column, a desorption column (for  $CO_2$  uptake and release), and a water pump that circulates the fluid. In this configuration, the water reservoir is integrated into the desorption column, as this simplifies the design.

To appropriately dimension the absorption and desorption tanks, a defined biogas flow rate is required. However, as noted in the compressor design section, the exact flow rate has not yet been determined. Therefore, the water scrubbing system is provisionally designed to process an estimated unfiltered biogas flow of 20 sL/min. The setup aims to achieve a  $CO_2$  removal rate of 90%.

### 3.3.1 Absorption and desorption column

The core of the water scrubbing process is the absorption column, where the water flows counter-current to the gas stream, enabling  $CO_2$  to dissolve into the liquid phase. According to [59] there are 10 general factors that influence the dimensions of an absorption column. They are:

- the input gas and its parameters,
- recovery rate,
- absorbent material,
- operating conditions,
- absorbent flow rate,
- number of Transfer Units (NTU),
- temperature,
- type of absorber,
- column height,
- column diameter.

Some of these factors, such as temperature and input conditions, are fixed. This calculation aims at a 90% efficiency (influenced by NTU) and will work with water as an absorbent. This section will focus on determining the optimal column height, column diameter, working pressure, and absorbent flow rate.

A fully theoretical model of a scrubber unit requires numerous system-specific constants and parameters that are difficult to determine and verify accurately within the scope of this project. Therefore, a more practical calculation is proposed in [59], using Billet-Schultes correlations. This method requires four criteria to be met:

- maximum diameter of 5 cm,
- low pressure drop inside the column,
- no corrosion considerations,
- low liquid holdup.

This project will use this 5 cm maximum diameter as this is a practical size. Low pressure drop and low liquid holdup will be reached as no packing is used in this project. The design of a reciprocating compressor will push the gas in the column in the form of bubbles. This itself will deliver a high contact area between the water and the gas, and thus packing material is not required. The corrosion effects of the scrubber walls are a concern when working with metal-walled scrubbers, for this setup, this will be avoided by using plastic or corrosion resistant materials for the scrubber walls.

The first constant is the Height of a Transfer Unit (HTU). This represents the length over which the driving force drops by a factor of  $1/e$ . In this case, the driving force is the pressure difference between the partial pressure of  $CO_2$  and its equivalent value in water. This force is calculated according to (3.3). HTU is determined using the cross-sectional area ( $S$ ), the Phase Mass Transfer Coefficient ( $K_g a$ ) and the molar vapor flow rate ( $V$ ).  $S$  and  $V$  are calculated based on given assumptions and prior data, namely a column diameter of 5 cm and a molar mass flow of 20 SL/min. However,  $K_g a$  is more complex to estimate. This constant relates to the diffusion of  $CO_2$  into the liquid phase. It is mostly dependent on bubble size, turbulence and pressure difference. Typically, this value ranges between  $0.1s^{-1}$  and  $0.01s^{-1}$  for a system at 8 bar [59]. The bubble size for this system is hard to predict, as an initial estimation, this design assumes  $0.05s^{-1}$  as the value for  $K_g a$ . In the testing phase, this should be verified and adjusted if needed.

$$HTU = \frac{V}{K_g a \cdot S} \quad (3.3)$$

Secondly, the number of transfer units (NTU) determines the amount of HTU required to reach the required removal level and is calculated by equation (3.4). Using this equation and requiring a 90% removal efficiency, the minimum required NTU is 2.30.

$$NTU = \ln \left( \frac{c_{in}}{c_{uit}} \right) \quad (3.4)$$

These calculations show that the HTU is 0.31 m. The full length ( $l_{tot}$ ) of the scrubber is the product of NTU and HTU. After calculating NTU and HTU, the total height of the absorption column should be at least 0.80 m. In practice, this column will have additional losses, leading to a higher needed efficiency.

$$l_{tot} = NTU \cdot HTU \quad (3.5)$$

The optimal fill level in an absorption column is crucial to ensure efficient gas-liquid contact [59]. This level depends on both gas and liquid flow rates. Although lower water levels can enhance efficiency, excessive gas volume within the column can create a dead zone, resulting in longer startup times and increased gas losses during maintenance. To mitigate these issues, the system should be designed with a higher fill level, minimizing the dead zone while maintaining sufficient space for gas flow. This balance, initially set at 90%, optimizes performance and operational stability. This level will have to be evaluated and further optimized during the testing phase.

## Desorption column

The desorption column can follow the same design principles as the absorption column, but to simplify construction it also houses the water reservoir. By combining these two functions, the desorption time for  $CO_2$  to strip out of the water is extended, boosting overall desorption efficiency.

Rather than introducing an air stream through the column, a more economical approach involves spraying pressurized water above the reservoir so that the water is mixed well with the air. This increases the liquid–gas interfacial area, promoting  $CO_2$  transfer into the gas phase without the need for an air blower. The principal drawback of this method is the corresponding rise in evaporative losses. A second drawback is that, because there is no forced airstream, the air above the reservoir might, after running for extended periods of time, have an increased  $CO_2$  concentration. This lowers the efficiency of the desorption column. Good ventilation is thus important around this desorption column.

### 3.3.2 Water pump

The water pump transfers water from the desorption tank to the top of the water scrubbing column. When the system operates at 8 bar, the pump must overcome the pressure differential and provide adequate water flow.

The required water flow is mainly dependent on the difference in the partial pressure of  $CO_2$  between the water scrubbing and desorption tanks. The  $CO_2$  concentration does not directly affect the required flow rate, as a higher concentration results in a higher partial pressure, thereby enhancing the removal capacity of the water. Figure 3.5 illustrates the minimum water required to purify 1 L of biogas at 8 bar, using Henry's law to determine the water's removal capacity [59]. In the desorption tank, air occupies the space above the water, which has a low partial pressure of  $CO_2$ . During the process,  $CO_2$  dissolves out of the water into the air. Therefore, adequate ventilation is essential to maintain a low  $CO_2$  partial pressure directly above the water. If there is insufficient ventilation, and the partial pressure of  $CO_2$  rises, The removal efficiency will be lower.

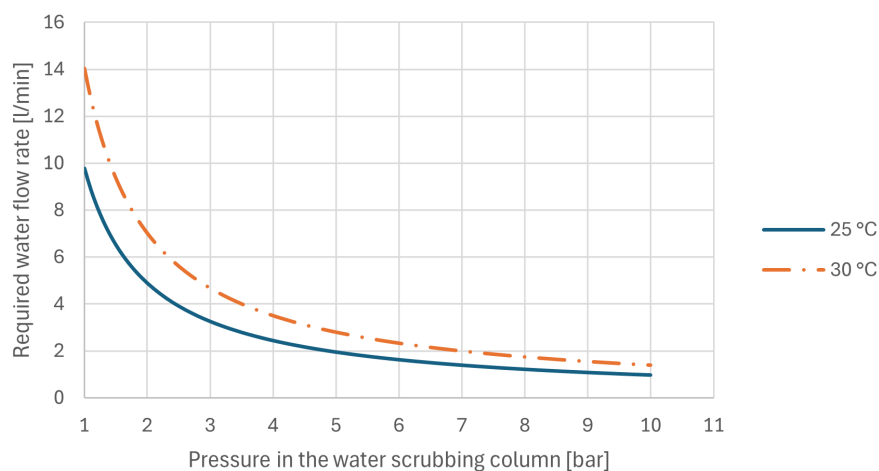


Figure 3.5: Minimum required water flow in function of the water scrubbing pressure

Figure 3.5 compares the minimal required water flow rates at 25 °C and 30 °C, given a removal efficiency of 90%. At higher temperatures, the water's absorption capacity decreases [59], necessitating a higher water flow rate. The operational temperature during this project is expected to be between these two values.

The higher the pressure difference, the less water is needed. If the pressure inside the tank is constant, a fixed amount of water is needed. For example, at a pressure of 8 bar, 1.8 L is the minimum. However, if there is no pressure relief valve, the pressure will start low and then increase while the system operates. A variable amount of water will be needed or the purity of the output will vary. If the water flow is kept constant, the process will initially yield lower purification efficiency, improving as the pressure increases. If the process just started, the absorption capacity of the water already present in the column can also influence the removal efficiency at the beginning of the processes.

Increasing the maximum pressure enhances the  $CO_2$  solubility in water, allowing for a greater volume of  $CO_2$  to be dissolved at a given pressure. Consequently, this leads to a higher concentration of methane within the same volume, resulting in an increase in the energy density of the compressed gas. As a result, the operational lifespan of a single tank of gas is extended.

## 3.4 Absorption setup

As an alternative to water scrubbing, absorption can be used. This section will discuss the design of this absorption column.

First, the absorption substance and the needed amount of absorbent will be determined. Afterwards, the column will be designed, based on comparable setups and physical models. The column will be exposed to 8 bar of pressure.

### 3.4.1 Absorption material

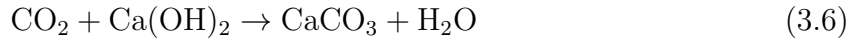
In the literature study, several options for absorption materials were evaluated.  $Ca(OH)_2$  was identified as the most suitable material for use in this specific rural context.

The system will be operated in batch mode. Continuous operation would require additional components, such as an additional pump to circulate the absorbent solution, which would increase both energy consumption and associated costs. Batch operation significantly reduces these costs and complexity, making it a more appropriate choice for decentralized, small-scale applications.

In conventional setups, a stirrer is often employed to ensure proper dissolution of  $Ca(OH)_2$  in the liquid phase. However, incorporating a mechanical stirrer would add considerable expenses, particularly due to its electricity demand. Therefore, this design proposes to operate without mechanical stirring. Instead, the biogas will be introduced at the bottom of the absorption column via a compressor. The rising gas bubbles are expected to promote sufficient mixing of the absorbent solution. If this proves insufficient, a stirrer can still be implemented during the testing phase.

The frequency and quantity of  $Ca(OH)_2$  replenishment can be determined based on the biogas production rate. An approximate daily production of 100 L of biogas is expected, containing an estimated 40 L of  $CO_2$ . Assuming the biogas enters the system at 1 bar and a temperature of 30 °C, the corresponding amount of  $CO_2$  can be calculated using the ideal gas law. This results in approximately 1.27 moles of  $CO_2$  per day.

The absorption reaction follows:



Thus, 1.27 mol of  $Ca(OH)_2$  is required per day. Given the molar mass of  $Ca(OH)_2$  (74 g/mol), this corresponds to approximately 94 g per day. Accounting for material losses, a conservative daily requirement of 100 g of  $Ca(OH)_2$  is considered. However, this has to be verified during implementation.

If the absorbent is replenished weekly, a single batch would require approximately 700 g of  $Ca(OH)_2$ .

### 3.4.2 Absorption column

In typical absorption column design, the column height is determined through differential mass balances, relying on experimentally determined parameters specific to the packing material and fluid properties [122].

$$dy = \frac{K_G \cdot a_e \cdot P}{G} (y - y^*) dz \quad (3.7)$$

$$dx = \frac{G}{L} dy \quad (3.8)$$

Where  $y$  is the mole fraction of  $CO_2$  in the gas phase,  $y^*$  is the equilibrium mole fraction of  $CO_2$  corresponding to the bulk liquid phase composition, and  $dz$  represents a differential column height. Pressure  $P$ , gas molar flux  $G$ , liquid molar flux  $L$ , global gas-phase mass transfer coefficient  $K_G$ , and effective specific interfacial area  $a_e$  are considered constant along the column. The variable  $x$  denotes the total molar concentration of all dissolved carbonic species, including  $CO_2(aq)$ ,  $H_2CO_3$ ,  $HCO_3^-$ , and  $CO_3^{2-}$ .

However, the present setup does not make use of structured packing. Instead, gas-liquid contact occurs in a bubble column, where the interfacial area  $a_e$  is not predefined. In such systems, mass transfer is governed by hydrodynamic factors such as bubble size, residence time, and the geometry of the reactor. As a result, conventional design methods based on the height of a transfer unit (HTU) or height equivalent to a theoretical plate (HETP) are not directly applicable.

Since detailed modeling tools such as CFD or population balance models are unavailable, performance must instead be estimated using empirical correlations from literature [123]. Although capturing all physical processes in a bubble column is complex, several simplified expressions provide useful insights into reactor behavior [124].



First, the superficial gas velocity  $U_G$  is defined by the ratio of gas flow rate  $Q_G$  to column cross-sectional area  $S$  [123].

$$U_G = \frac{Q_G}{S} \quad (3.9)$$

Secondly, the gas holdup  $\varepsilon_G$ , can be expressed in terms of superficial gas velocity  $U_G$  and captures how much gas is being held in the column at any given time.

$$\varepsilon_G = \frac{U_G}{0.3 + 2U_G} \quad (3.10)$$

Assuming roughly spherical bubbles of Sauter mean diameter  $d_{32}$ , the interfacial area per unit volume  $a_e$  follows.

$$a_e = \frac{6\varepsilon_G}{d_{32}} \quad (3.11)$$

Finally, the overall mass-transfer coefficient  $K_g a$  is simply the product of the liquid-film coefficient  $k_L$  and the interfacial area  $a_e$ .

The purification of  $CO_2$  using a solution of  $Ca(OH)_2$  can be achieved in a relatively compact reactor. Previous studies have successfully demonstrated this approach [68], [125]. An example setup is shown in Figure 3.6.

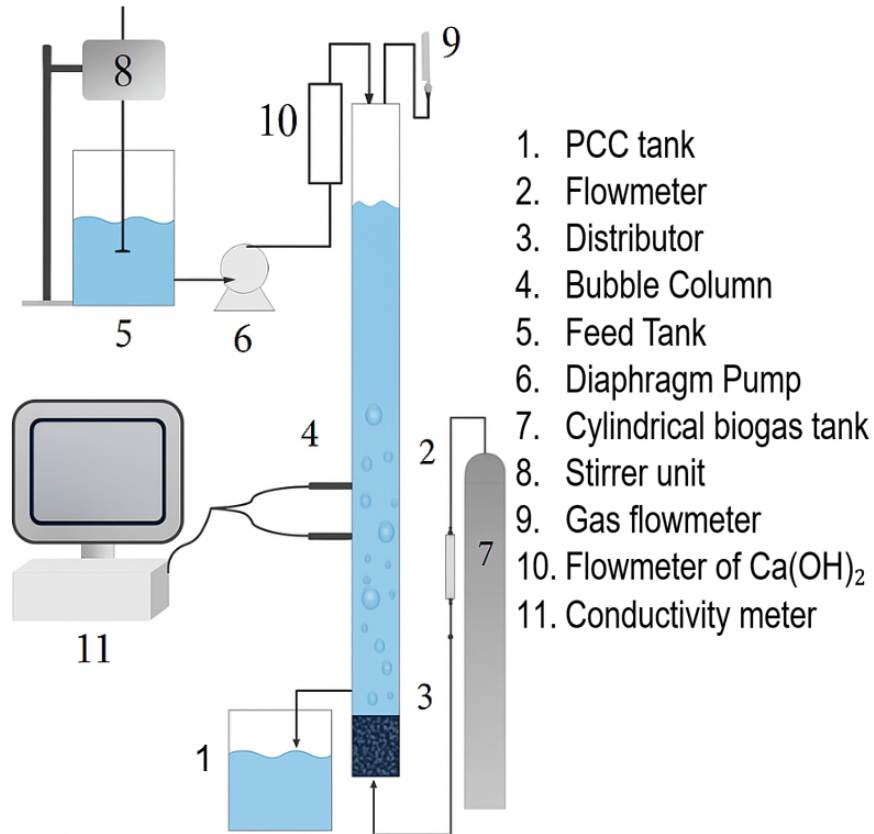


Figure 3.6: Absorption setup [68, p. 287]

The depicted system uses a column with an internal diameter of 7 cm and a height of 100 cm. Under these conditions, approximately 70% of the  $CO_2$  in biogas was removed using countercurrent contact with a flowing  $Ca(OH)_2$  solution. Operating conditions included a concentration of 3.06 g/L, a liquid flow rate of 200 mL/min, and a liquid height of 50 cm.

In contrast, the proposed system will operate in batch mode without a continuous supply of fresh  $Ca(OH)_2$ . This will likely reduce overall absorption efficiency. To compensate, a taller reactor is preferred, with a target height exceeding 150 cm. The column diameter will remain close to 7 cm, matching the configuration in [68].

The setup will try to use only one compressor. The compressor will be placed before the absorption column. This means the pressure in the reactor will be as high as the pressure of the output biogas. This elevated pressure is expected to enhance mass transfer efficiency due to bubble breakage, which increases the interfacial area  $a_e$  [126].

The flow rate will depend on the flow rate delivered by the compressor. The lower the flow rate, the lower  $U_G$  and the higher the efficiency will be.

## 3.5 Post processing

After exiting the absorption column or water scrubbing column, the gas will be saturated with water absorbed during the scrubbing process. To remove this moisture, the gas will first pass through a moisture trap. Following dehydration, the gas will be stored in an LPG container. Proper sizing of the storage container is critical to ensure both operational efficiency and economic feasibility.

Before entering the LPG tank, the gas must be analyzed. First, the pressure should be continuously monitored. This provides the operator with real-time information on the storage pressure, helping to determine when the system should be shut down to avoid overpressurization. Secondly, the composition of the gas should be measured, preferably continuously. A biogas analyzer will therefore be integrated into the system at this stage, giving real-time assessment of gas composition prior to storage.

### 3.5.1 Moisture removal unit

Similar to the preprocessing stage, a moisture removal unit is added. This unit serves the same purpose of removing moisture from the system. This is done by locally expanding the biogas stream. However, this moisture removal unit has the additional purpose of catching any liquid water introduced by turbulence or pressure fluctuations. The water column should be properly sized, as the moisture, especially in combination with small amounts of  $H_2S$ , can corrode and degrade downstream components.

If even lower moisture levels are required, an optional post-condensation phase involves the use of silica gel crystals. These are capable of adsorbing the remaining water vapor, ensuring a sufficiently low humidity level in the final gas mixture. The inclusion of a silica gel stage can extend the operational life of the gas system, as it minimizes the need for maintenance caused by moisture-related wear.

By pre-filtering with a moisture trap, the operational lifespan of the silica gel is significantly extended, thereby reducing the system's maintenance frequency and operational costs. While the silica gel needs occasional regeneration or replacement, the system's reliance on it can be minimized by maintaining effective condensation at the initial moisture trap. However, this causes an additional cost and maintenance for the system, and therefore this project will not implement the chemical drying.

The post-scrubbing moisture trap is sized similar to the preprocessing unit. Assuming the temperature of this gas is the same, the amount of captured water will be the same as the preprocessing unit. This leads to a condensation of  $23.6 \text{ g/m}^3$ . Given a weekly amount of biogas of 700 L, the total amount of liquid will be 16.5 ml.

In addition to this, an occasional slug of liquid water can occur during operation. When using the absorption setup, these slugs are less likely to occur as no water gets added during the process. The water scrubbing setup, however, might see more water entering the gas lines as water is constantly added to the system. Fine-tuning the recirculation flow rate should ensure that excess water never accumulates during normal operation.

Overall, a combination of condensation and water slugs should be taken into account when dimensioning the unit. Since the amount of water coming from slugs is hard to estimate, this will be determined experimentally in the implementation phase.

### 3.5.2 Gas storage

The produced gas will be stored in standard LPG containers, which are widely available even in rural areas. Several factors influence the choice of container size. On one hand, the container must be large enough to store sufficient gas to cook at least one meal. On the other hand, it should not be excessively large, as affordability is critical to enable local households to purchase a container without making a substantial investment. Additionally, the container should ideally be capable of holding at least one day's worth of gas production.

The first aim is to have a container of LPG which can at least provide power for one cooking session. Pure methane will not be reached in this project, but it can be used as a tool to make an estimation of the amount gas needed to cook a meal. Methane has a heat value of around 50 to 55 MJ/kg [127]. In Tanzania, a study proved that, using LPG, around 1 MJ of gas is used to cook a meal per person [128]. Energy losses from cooking with LPG, in comparison to methane, are assumed to be similar. This same study found that a meal is cooked for around 4 persons on average. This would mean there would be at least 4 MJ of gas required to cook a meal, this is a very rough estimate, but it could be used to make preliminary estimations.

Translating this to methane consumption, 4 MJ corresponds to about 80 g of methane. If the storage pressure is set below 8 bar and the ambient temperature is around  $30^\circ\text{C}$ , the required tank volume can be estimated using the ideal gas law. Under these conditions, approximately 15.7 L of storage volume would be needed to store the amount of methane required for one meal.

On the other hand, a single daily withdrawal of 100 L of raw biogas at 1 bar corresponds to approximately 60 L of methane. This is assuming 60 vol%  $CH_4$ , under storage conditions of 8 bar at 30 °C. Using the ideal gas relationship, this volume compresses to 7.5 L. This amount is insufficient for one full meal, implying that roughly two days of gas production would be necessary to cook a single meal.

When considering this bigger, fixed-dome, digester, the output biogas is to be expected at 6,500 L per day. This would, under the same conditions as before, compress to 490 L of pure methane. This size of a tank would be too big and not practical. The gas would have to be compressed into multiple smaller tanks at the same time. A total output of 490 L pure methane per day would translate to around 31 meals per day.

It is important to note that the calculated container volumes are theoretical minimums. In practice, larger containers should be selected to account for real gas behavior, safety margins, imperfect system efficiencies, and fluctuations in gas production.

## 3.6 Energy supply

The energy requirements of the system will be fully supplied by solar energy. The solar energy system will constitute a significant portion of the overall project cost. Consequently, all energy-consuming components must be selected and operated in a way that minimizes total energy consumption.

Besides the energy demands of the project itself, additional energy consumption is expected in the future. For example, lighting for site security will likely be installed after the project concludes. Consequently, the solar energy system must be oversized to account for additional loads in the near future.

Another important consideration is the high inrush current drawn by devices such as the compressor and the water pump during startup. The solar system must be capable of handling these currents. It is likely the system will only be able to start during periods of peak sunlight.

### 3.6.1 Solar panels

Monocrystalline and polycrystalline panels are both widely available options. A choice has to be made based on efficiency and cost. Monocrystalline panels generally offer higher efficiency and better performance in high-temperature conditions, which suits the project's climate. Although slightly more expensive, monocrystalline panels are therefore preferred for this project. But the ultimate choice depends on local availability. The total energy requirement for the Kimbiji site will be estimated once the university setup is running. This ensures the power supply will be in accordance with the energy demand of the required components.

The energy consumption of the site, in addition to the energy used for this project, will be estimated at around 200 W. This will be incorporated into the design.

### 3.6.2 Battery pack

A battery storage system is required to ensure continuous operation despite weather variability. Without a battery, the system would be highly vulnerable to even minor fluctuations in solar irradiation, potentially causing shutdowns.

In the literature study, two main battery types were considered: lithium-ion and lead-acid. Lithium-ion batteries offered superior cycle life, energy density, and DoD. However, they come at a significantly higher cost. Given the small-scale nature of the project and the strong need to be economically viable, lead-acid batteries are selected.

Additionally, the inrush current can be expected to be around 6-8 times the nominal current of the load. A starter battery with should be used if available. These have generally more plates than a typical battery, offering a lower internal resistance, an thus, a lower voltage drop.

### 3.6.3 Inverter and controller

For this project, both components will be oversized. This design choice anticipates future expansions of the solar array to be able to supply more power. The solar panels will be dimensioned 200 W higher than the actual need. It could be the case that, in the future, the required additional power could be even higher.

Oversizing the inverter and controller provides flexibility and avoids costly replacements or upgrades later. Although a DC-to-AC ratio of 1.2 to 1.4 is typically used [129], this design applies a larger margin of 400 W above the estimated continuous load. This margin also ensures the power electronics can accommodate the motor inrush currents without auxiliary power sources. Either PWM or MPPT controllers may be used, depending on local cost and availability.

# Chapter 4

## University setup

This chapter outlines the development, implementation, and analysis of the university-based setup. The design and implementation of this system serve several objectives. First, it acts as a test platform for validating the functionality and robustness of the system prior to deployment in Kimbiji. Second, it enables a comparative study between two  $CO_2$  purification techniques: absorption and water scrubbing. Most importantly, the setup is intended as a long-term educational tool for students at the university. After the project's conclusion, it can continue to serve as a hands-on learning platform. The setup is supposed to be a starting point for iterative improvement by future students and researchers.

The chapter begins with a detailed overview of component selection, explaining the purpose of each part, the rationale for its use, and its relevance to the overall system. The two parallel configurations, absorption and water scrubbing, will be discussed. As these parts were bought in Tanzania, all prices are expressed in Tanzanian shilling (TZS). The prices given in euro are calculated using the exchange rate of 3,034.78 TZS/EUR of 08/06/2025.

The next section discusses the implementation process, detailing how the selected components are assembled and interconnected within the system. Attention is paid to ensuring a safe and educationally valuable setup. A dedicated subsection on knowledge transfer is included, which addresses the steps taken to ensure the continuation of the installation after the conclusion of the project. Important here are the local students who will continue to use the system, they will be trained to safely operate the system, understand its underlying principles, and recognize potential hazards.

The third major section describes the testing of the completed university setup. The testing focuses first on the  $H_2S$  removal unit and then compares the absorption and water scrubbing setup. This section includes a methodology, experimental results and a critical discussion.

Finally, the chapter concludes with a comparison between the absorption and water scrubbing systems, providing insights that will construct the final design of the installation in Kimbiji.

## 4.1 Component selection

This section outlines the selection process of components used in the university-scale biogas upgrading and compression system. The choices were made with consideration for technical suitability, cost-efficiency, and availability within the local context of Dar es Salaam.

Most components were sourced from the Kariakoo market, the largest and most diverse commercial hub in the city. Given Dar es Salaam's status as one of East Africa's major port cities, Kariakoo benefits from a wide range of locally sold and imported goods. Purchasing materials directly from this market ensured minimal cost and immediate availability. In the further component selection, if the origin of a part is not specified, it can be assumed that it is bought in Kariakoo.

One notable store in Kariakoo is 'Oceanic Biogas Appliances', known for supplying parts for biogas projects. The project also sources parts from this reputable, cheap, and reliable company.

Certain specialized components, such as calcium hydroxide  $Ca(OH)_2$ , were acquired through Ardhi University or external academic and professional networks. Additional minor parts were sourced from various local hardware stores, depending on availability.

A full overview of selected components and their prices is added in Attachment A. All prices are inclusive of value-added tax (VAT) and reflect the amounts paid during local procurement. It should be noted that prices may be elevated compared to those typically paid by local residents, as components were acquired through local retail outlets by foreigners. The list is divided into five sections: preprocessing, water scrubbing, absorption, post processing, and energy supply.

### 4.1.1 Preprocessing

The preprocessing stage prepares the raw biogas for subsequent purification and storage. It includes three critical components: a moisture trap to remove water vapor and condensate, an  $H_2S$  filter to eliminate hydrogen sulfide and a compressor to raise the pressure of the gas for storage and  $CO_2$  removal. This stage is essential to protect the system components from corrosion, as discussed in the literature study, the  $H_2S$  in combination with liquid water causes high corrosion.

#### Moisture trap

To eliminate condensate and water vapor, a biogas-specific dehumidifier is used. This part was sourced from the biogas-specific store. Since other projects at Ardhi university which used this part did not experience any issues, the same part and supplier were selected again. This moisture trap is illustrated in Figure 4.1(a).

The trap can comfortably retain up to 0.5 L of liquid water. Since the expected quantity of moisture is low, this will suffice. The unit is priced at TZS 5,000. Designed for ease of maintenance, it features a simple drain valve for periodic removal of collected condensate. The part is not designed to handle high pressures. Since the university setup and Kimbiji setup will both be based on a floating-drum digester, the pressure will be low.

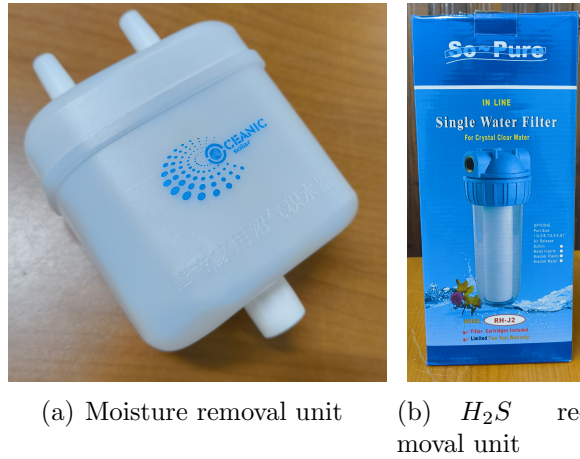


Figure 4.1: Pre processing components

### $H_2S$ removal unit

For  $H_2S$  removal, a container is required with two ports for gas inlet and outlet. It also needs to be easily opened for replacement of the absorbent material. Ideally, the container would be transparent to allow for visual monitoring of the absorbent's saturation. Alternatively, a container can be built from plexiglass or PVC piping. However, considering cost and time, an already existing part is used.

A modified water filter housing was selected as the container. Since water filtration is a common practice, these housings are readily available. Figure 4.1(b) shows the water filter used in this setup, this includes an ungrooved PP fiber cartridge to filter sediment out of water. By removing the original filter element and filling the transparent casing with a suitable absorbent, the system allows continuous visual monitoring of the absorbent's saturation without interrupting operation. Brass gas nipples are used to connect the unit to gas lines, these nipples cost TZS 5,000 each. The housing can be easily unscrewed for absorbent replacement. The filter, purchased from a shop in Kariakoo, cost TZS 30,000. Although relatively expensive, its ease of use justified the cost. It can be argued that constructing the unit from raw materials would have been both more expensive and less reliable.

Four absorbent materials were selected for comparison, as illustrated in Figure 4.2.

Steel wool was selected as a cheap and readily available material, priced at TZS 500 per 15 g and purchased from a local supermarket. This particular type is chosen because it is believed to be untreated. The second and third options were purchased from the previously mentioned biogas supplier. These included iron oxide pellets, typically used as filter media in commercial  $H_2S$  filters, priced at TZS 5,000 for 750 g. The other material was activated carbon granules, which were priced relatively high at TZS 35,000 for 1 kg. The fourth option is rusted steel wool. This rusted material can be considered a waste product, and its cost is therefore negligible. For this project, the normal steel wool was pre-oxidized by soaking it in water and exposing it to air, allowing it to rust. The cost of this method is equivalent to that of untreated steel wool. These four absorbents will be evaluated during the testing phase.



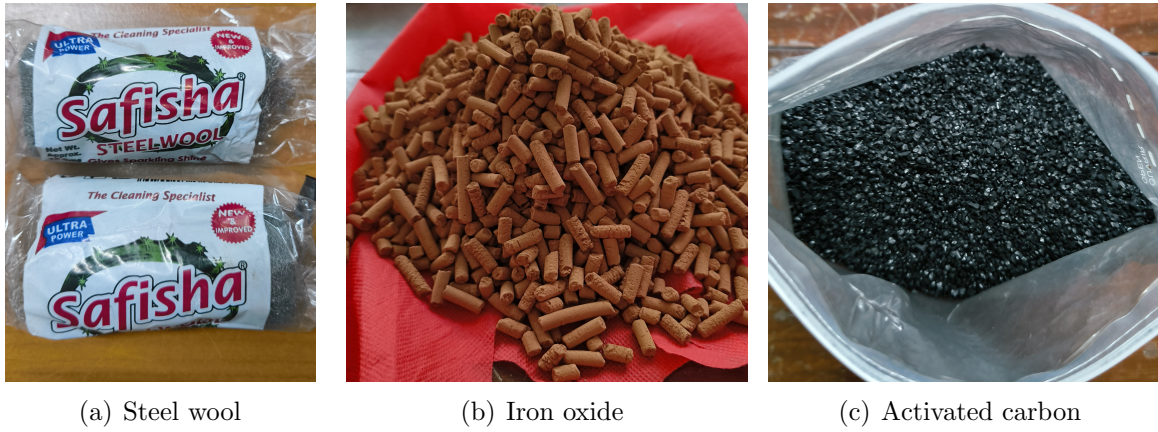


Figure 4.2:  $H_2S$  removal materials

## Compressor

To achieve the required gas compression, a pressure of 8 bar must be reached. Although the precise flow rate is not fixed, it can be adjusted depending on budgetary constraints. A critical design requirement is that the selected compressor must tolerate the presence of liquid phases in the gas stream, which can occur due to the condensation of water vapor during biogas compression.

Initially, a standard HVAC compressor, normally used for building cooling, was considered. However, even the smallest available unit, priced at TZS 600,000, exceeded both the technical requirements and financial limitations of the project. Subsequently, R134a refrigeration compressors were evaluated as a viable alternative. These compressors are commonly used in domestic and commercial refrigeration systems, and are specifically designed to withstand intermittent liquid flow due to refrigerant condensation. Their internal construction, typically reciprocating, allows operation at relatively high pressures while maintaining durability and reliability.

Since flow rate is directly related to compressor displacement, the selection focused on finding a cost-effective compromise between volume flow rate and affordability. Multiple compressors were available, [130] gives an overview of the different models. The ADW43 model was chosen, with a displacement of  $4.3 \text{ cm}^3$ . This model was available at a low price relative to its displacement. The selected compressor, priced at TZS 141,000 is shown in Figure 4.3.

The compressor's refrigerant ports use standard brass fittings, which can be brazed onto copper tubing. However, due to the absence of brazing equipment, the compressor will be connected using high-pressure air tubing secured with hose clamps. Testing will verify the leak tightness and mechanical robustness of this solution.

To mitigate structure-borne vibration, the ADW43 is mounted on neoprene rubber cushions. These vibration isolators reduce wear due to vibrations and minimize noise transmission. Additionally, the compressor housing incorporates a service port, useful for oil level inspection.

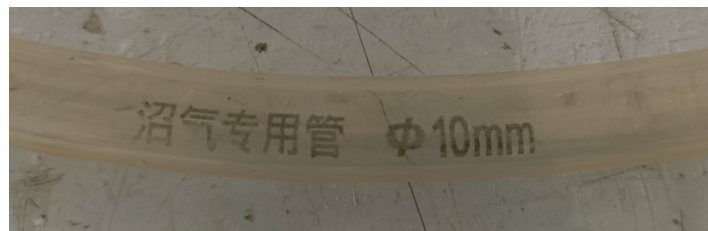


Figure 4.3: Refrigeration compressor ADW43

This model has a power usage of 110 W. This translates to current of around 0.5 A. Like most resistance-start, induction-run (RSIR) hermetic motors, the ADW43 exhibits a high inrush current at start-up. A locked-rotor current can be expected in the order of 5 to 10 times the nominal running current. This means that since the nominal current is 0.5 A, the starting current will be 2.5 to 5 A. This will be a problem when the compressor is fed by solar energy. The actual inrush current should be measured during testing.

### Tubing

The tubing downstream from the compressor will be required to handle a pressure of 8 bar. Earlier projects have used specific biogas tubes, able to withstand 8 bar. However, this high-pressure tubing was not available anymore. For the low-pressure side, a similar tubing was selected, not able to withstand high pressure, the tubing is illustrated in Figure 4.4(a). The tubing has a 10 mm diameter.



(a) Low-pressure tubing



(b) High-pressure tubing

Figure 4.4: Biogas tubing

As high-pressure tubing, a high-pressure air hose was selected. This tube has a sturdy construction and is made to handle a working pressure of 8 bar. It has a bursting pressure of 80 bar. The tubing, illustrated in Figure 4.4(b), costs TZS 6,000 per meter. The setup uses this tubing in both the 8 mm and 10 mm sizes depending on the specific connection.

### 4.1.2 Absorption Setup

The absorption setup consists of a water column with calcium hydroxide ( $Ca(OH)_2$ ) dissolved in the water. Biogas is directed through this column to enable the absorption process. The design includes a provision for batch-based replenishment of  $Ca(OH)_2$ , and the column must be constructed to accommodate this functionality. A mechanical stirrer will not be included in the initial design. It is assumed that the turbulence generated by the inflowing biogas will provide sufficient mixing and dissolution of the  $Ca(OH)_2$ .

The column will be constructed using high-pressure PVC piping. This material is widely available, modular, and suitable for high-pressure applications. Various components such as valves and end caps can be easily integrated into the system using this PVC standard.

Class C PVC piping, capable of withstanding pressures up to 9 bar at ambient temperature, will be used. This is the highest pressure class commonly available and ensures adequate durability. The adhesive selected is also rated for high-pressure use to ensure leak-free joints.

PVC piping is available in a variety of diameters, the largest diameter readily available is 2 inch. While the design calculations indicated that an optimal configuration would use a pipe of 7 cm in diameter and 1.5 m in length, the availability of 2 inch (5 cm) piping makes it a practical alternative despite a slight reduction in theoretical efficiency. Consequently, the absorption column will be constructed from 2 inch Class C PVC piping, as illustrated in Figure 4.5(a).



Figure 4.5: Implementation of the water scrubbing setup

To connect the gas tubing, a hole will be drilled into the end caps, which will then be threaded to allow the insertion of a screw-in gas nipple. Since only one hole is needed per end cap, threads can be made using a turning machine or a tap, depending on local availability.

The required components were found at the following prices: 6 m of high-pressure PVC piping for TZS 45,000; end caps at TZS 10,000 each; valves at TZS 45,000 each; and high-pressure adhesive at TZS 15,000 per 500 ml. These components are illustrated in Figure 4.5.

The absorbent was acquired through the lab equipment supplier of Ardhi University. It came at a cost of TZS 35,400 for 25 kg. The absorbent is illustrated in Figure 4.6. This bag contains high-quality pure  $Ca(OH)_2$ . The exact purity of this substance is unknown, so a wider safety margin should be taken into account when filling the column.



Figure 4.6: Bag of  $Ca(OH)_2$

### 4.1.3 Water scrubbing setup

The main components of the water scrubbing setup are the absorption column, desorption column, and the water pump.

#### Absorption and desorption column

The components of the water scrubbing column are equal to those of the absorption column from the absorption setup. PVC piping will also be used. The water scrubbing column will not need a valve, but will need two sets of connections, one for biogas and one for water. The holes in the end caps will thus be offset from the central axis, making them unsuitable for machining on a standard lathe. A tap will be required.

The desorption column is essentially a water tank, with the top of the tank open to allow air to access the surface, allowing for effective  $CO_2$  removal. For this purpose, a used water jug can be utilized. Figure 4.7 shows an 18 L water jug with the top cut off to allow for better airflow. These water jugs are used locally and often are disposed of. They are available for free and serve the purpose of this project well. This also aligns well with the main idea of the Kimbiji test site, where all waste is transformed and reused as a resource.





Figure 4.7: Modified water jug

## Water pump

The water pump required for this project must operate at a relatively low flow rate of 1.8 L while being able to achieve a high head pressure of up to 8 bar. This specific combination is relatively uncommon, and as such, various alternatives were explored. These included water pumps designed for large coffee machines, booster pumps for filtration systems, well pumps, pressure washers, and solar pumps. The booster pump and pressure washer were the most promising options. Since the booster pump did not come with high pressure connections and the complete filtration system was expensive, the project settled on using the pressure washer.

The selected pressure washer, as illustrated in Figure 4.8, is priced at TZS 220,000, which is higher than that of a typical booster pump (approximately TZS 150,000). It has a flow rate of 6,5 L/min and a maximum pressure of 100 bar. This greatly exceeds the required specifications. Nevertheless, considering the price, it is considered suitable for the purposes of this project.



Figure 4.8: Pressure washer

In addition to the pump itself, the pressure washer offers several advantages. It is easy to implement, as the necessary connections are included with the unit. Figure 4.9 shows the available connector on the high pressure side.

The connector is a standard connector designed to withstand high pressure. It can be connected to the end caps using a tube and a clamp. Furthermore, it comes with a high-pressure water hose, which adds to its overall utility.



Figure 4.9: Pressure washer connection

The pressure washer consumes 1.2 kW of power. This is significantly more than the compressor. The actual power consumption can be expected to be lower, since 100 bar of pressure will not be reached. Testing should confirm the actual energy usage.

#### 4.1.4 Post processing

The major parts of the post processing section consist of a moisture trap, a valve to control the gas flow to meet instrumentation, and an LPG tank.

The first element of the post processing unit is the moisture trap. Initially, the same water filter housing was implemented as used in the  $H_2S$  removal unit in the preprocessing (see Figure 4.1(b)). This time, the filter will operate under elevated pressure. The housing is rated for a maximum pressure of 125 psi (approximately 8.6 bar), which provides a small safety margin above the expected operating pressure of 8 bar. This should suffice.

After the moisture removal unit, a pressure gauge is installed. This gauge is able to withstand a pressure of 14 bar, and costs TZS 20,000. To permit continuous gas extraction for testing during operation, a brass valve is installed. The valve extracts gas from the high-pressure side and acts as an alternative output for the system. This valve is illustrated in Figure 4.10(a). The valve enables precise adjustment of the pressure differential between the high-pressure feed and the measurement side. The valve is rated PN20, which means it can withstand a pressure of 8 bar. The valve costs TZS 7,000.

The processed biogas is stored in a 15.6 kg LPG cylinder supplied by Taifa Gas, a leading LPG distributor in Tanzania. The tank is illustrated in Figure 4.10. This cylinder, one of the smaller sizes readily available, offers a nominal capacity suitable for precise measurements while minimizing biogas losses during each test. Its modest volume aligns well with the project's requirements. The acquisition cost of approximately TZS 20,000 positions it as an inventory holding cost rather than a capital investment, given its potential for resale and reuse. Furthermore, the system design allows for the sequential, or even simultaneous filling of multiple cylinders, facilitating larger distribution or storage requirements.

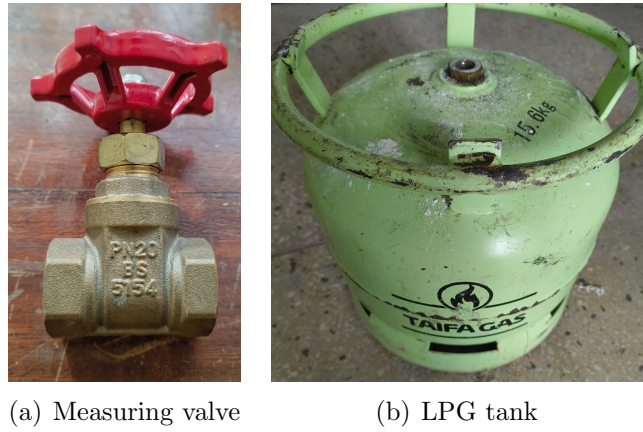


Figure 4.10: Post processing components

## 4.2 Implementation

This section describes the implementation of the university-scale experimental setup. The full setup, as illustrated in Figure 4.11, underwent several iterations before achieving its final configuration.

Biogas enters the system from a single inlet on the left, while two outlets on the right and in the middle direct the flow either to an LPG storage tank or to a measuring instrument.



Figure 4.11: Complete university setup

The system was installed adjacent to the biogas digesters, inside a building near the experimental hall. This facility serves as a development site where local students conduct their independent projects. It is an ideal location for this setup, as local students can assist as needed and upon completion of the initial setup, continue developing this setup after the project is concluded.



### 4.2.1 Preprocessing

The pre-processing arrangement is illustrated in Figure 4.12. Biogas is extracted directly from the digesters and conveyed to the test using a 3/8 inch garden hose.

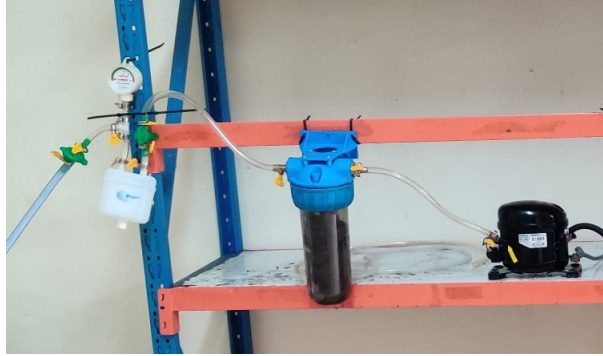


Figure 4.12: Preprocessing implementation

The initial section of the pre-processing unit comprises two biogas-specific valves, a pressure gauge, and the dehumidifier. The pressure gauge is calibrated to measure overpressure from 0 to 16 KPa, which is adequate for gas delivered by a floating-drum digester. The components are interconnected using the low pressure biogas hose, with stainless steel clamps applied at each connection point to ensure a reliable and gas-tight seal.

After exiting the dehumidifier, the biogas passes through the desulfurization unit, as shown in Figure 4.13. Brass nipples connect the hose to the inlet and outlet of the water filter. Inside the filter, a short section of garden hose replaces the conventional water filter and works to direct the gas flow to the bottom of the filter, ensuring maximum contact time with the absorbent medium. In Figure 4.13(b), the filter is filled with steel wool. However, this medium can be easily exchanged for alternative absorbents by unscrewing the bottom half of the unit. This will cause some biogas to be lost.



(a) Unscrewed top



(b) The full unit

Figure 4.13:  $H_2S$  removal unit implementation

Four materials were tested as absorbents: iron sponge, rusted steel wool, granulated iron oxide, and activated carbon. The total mass of absorbent placed in the column varied depending on the material. For iron sponge and rusted steel wool, the mass was influenced by the degree of compaction. Figure 4.13(b) shows an initial configuration using 60 g of iron sponge (four 15 g packets), while subsequent tests increased this to 180 g. When



granulated iron oxide was used, the column could accommodate approximately 1 kg of material. Activated carbon, due to its finer structure, allowed for a maximum fill of approximately 1.5 kg.

Finally, the biogas enters the compressor. The biogas hose and the compressor inlet have different diameters, 10 mm and 8 mm respectively. To bridge this mismatch, a short segment of the biogas hose was trimmed and adapted to fit the smaller inlet. The connection was secured using adhesive and a hose clamp to ensure gas tightness.

The compressor is capable of delivering a pressure of up to 8 bar. However, if residual gas keeps the outlet pressure high, the compressor fails to initiate operation, indicating a lack of start-up capability under backpressure. Additionally, the unit exhibits significant thermal buildup during operation. Once overheated, a thermal protection state is activated and cannot be restarted until adequately cooled.

The full preprocessing setup cost approximately TZS 237,730 (EUR 78.34). Added to this cost is the price of the  $H_2S$  removal material. This cost, for one week of biogas production, is TZS 1,166 (EUR 0.38) for the steel wool, TZS 400 (EUR 0.13) for the iron oxide pellets, or TZS 7,000 (EUR 2.31) for the activated carbon granulates. The full overview of components and their prices is in Attachment A.1.

## 4.2.2 Absorption setup

After the biogas is compressed, the gas passes through the absorption column. In the assembly of the absorption column, the most challenging part is achieving an airtight connection at 8 bar. The connection between the PVC tubing and the biogas tube proved to be the most difficult. The first idea was to drill holes directly into the endcaps and tap threads into the holes, using PTFE string to make it water and airtight. Ardhi university, or any other nearby universities, did not have the equipment to tap these threads, as the threads were imperial size, which is not common.

An alternative solution was found in a PVC supply store. This part is shown in Figure 4.14(a)

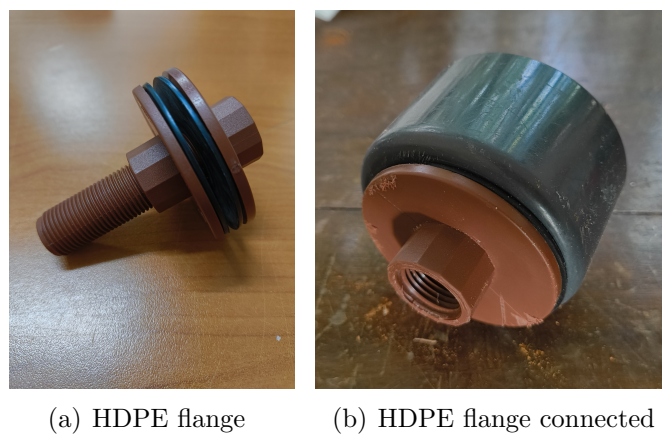


Figure 4.14: HDPE flange implementation

This part consists of a hollow tube and has two flanges with rubbers on it. This tube would be fitted in a hole in the endcap and a rubber can make a watertight and airtight

seal at both sides of the endcap. This assembly is shown in Figure 4.14(b). At the outside, a brass nipple can be attached to connect to the tubing. This proposal was tested at 8 bar pressure, but small leaks could not be avoided. Therefore, this connection is not implemented.

The next option, also from a store in Kariakoo, is a connector which can be glued to the endcap directly. The connector is shown in 4.15(a)

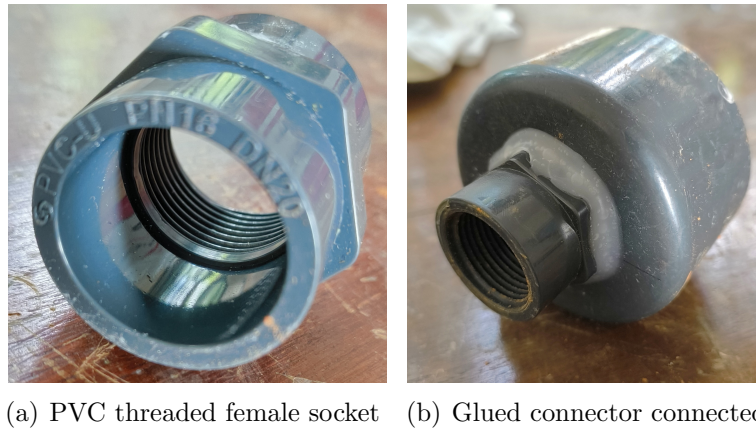


Figure 4.15: PVC threaded female socket implementation

This glued connection successfully withstood a pressure of 8 bar without any leaks. However, a notable disadvantage was that some connections exhibited leaks during initial pressure tests. After redoing these connections, however, the system performed reliably without further issues.

In the final layout, the connections are implemented as described. The full column has an overall height of 172 cm from one endcap to the other. The bottom part, made for replacing used  $\text{Ca(OH)}_2$ , has a length of 12 cm. Figure 4.16 shows the bottom part of the absorption column.

The valve at the bottom of the column can be closed. When it is closed, the bottom part of the column can be screwed off. This gives us the ability to remove old  $\text{CaCO}_3$  and add new  $\text{Ca(OH)}_2$ . The bottom part is sufficiently long for at least 700 g of  $\text{Ca(OH)}_2$  to be added.

Direct injection of biogas through the inlet tubing produces bubbles, due to the compressor's reciprocating build. However, these bubbles will have a larger size. To enhance gas-liquid contact and increase interfacial area, a simple perforated diffuser was fabricated by puncturing a plastic sheet with a fine needle. This inexpensive modification should generate smaller, more uniform bubbles, thereby increasing the interfacial area.

The column is larger than originally discussed in the design. The water fill level can be varied. This should be tested and evaluated.

The total material cost of the implemented absorption system is TZS 110,600 (EUR 36.44). The replacement cost of the  $\text{Ca(OH)}_2$  costs TZS 1,400/kg of material (EUR 0.46)



Figure 4.16: Absorption column

### 4.2.3 Water scrubbing setup

The water scrubbing absorption column is constructed similarly to the absorption unit, but with two key modifications: it omits the internal valve assembly and incorporates two pairs of outlets, one for biogas and one for water. There are two separate outlets at the top and the bottom instead of a single exit port, as illustrated in Figure 4.17(b). The full height of this column is 136 cm. The assembled configuration of the water scrubbing system is shown in Figure 4.17(a) and Figure 4.17(c).



(a) The top of water scrubber



(b) Dual exit endcap



(c) Desorption column

Figure 4.17: Implementation of the water scrubbing setup

The additional outlet at the top of the column, as visible in 4.17(a), is coupled to a high-pressure supply line coming from the pressure washer. This is connected via a short segment of the high pressure 10 mm tubing and a nipple, secured with stainless steel hose clamps. Alternative approaches, such as directly attaching the washer’s spray nozzle to the endcap using glue were evaluated but proved to be unreliable under high pressures.

The additional lower outlet, visible in Figure 4.17(c), serves as the drainage port for the  $CO_2$  rich water. Immediately downstream of this port, a valve is installed to regulate the flow rate exiting the scrubbing column and thereby the liquid level within the column. The valve and the scrubber are connected using a 10 mm nipple and a short piece of high-pressure hose.

After passing through this control valve, the  $CO_2$  rich waste water is discharged into the water jug, as illustrated in Figure 4.17(c). Here, the water collects and has time to discharge the  $CO_2$ . From this reservoir, the water is withdrawn by the pressure washer through a flexible 3/8 inch water hose and recirculated back into the upper inlet of the scrubbing column.

When the system is turned off, there will be no water present in the scrubbing column. Before biogas can be purified, the water level in the column should be brought to the desired level first. To estimate the water level in the water column, two markings were made on the outside of the water jug. The blue marker is located at the water level when the column is empty. This is the level at which the water must be filled before the system starts up. The red level indicator is at a water level that is 3 L lower. This level indicates that the water column is full, as the assembled column has a volume of 3 L.

The total material cost of the implemented water-scrubbing system is TZS 308,360 (EUR 101.61). This is substantially higher than that of the absorption unit, largely on account of the high-pressure washer. However, because this configuration requires no expendable absorbent media, its ongoing operational expenses are significantly lower.

#### 4.2.4 Post processing

The post processing unit is located immediately downstream of the absorption and water scrubbing columns. Figure 4.18(a) illustrates the complete configuration. The connection between the post processing unit and the columns is similar to that between the compressor and the columns. That is, an air hose connects to a brass fitting at the top of the column, clamped down. The hose can be connected to either of the two systems.

The first major component is the moisture trap, which is assembled in the same manner as the  $H_2S$ -removal unit used during preprocessing. Its connectors measure 15/16 inch in diameter, but locally available adapters only reduce to a nipple with a minimum diameter of 10 mm. Therefore, a 10 mm fitting was installed between the column outlet and the moisture trap inlet. Downstream of this fitting, an 8 mm hose was force-fitted over the 10 mm nipple, resulting in a very tight, yet functional, seal.

During preliminary testing, this unit initially failed to withstand the 8 bar pressure requirement. It was therefore replaced with an alternative model from the same water filter series (Figure 4.18(b)), which incorporates longitudinal reinforcement ribs and accom-

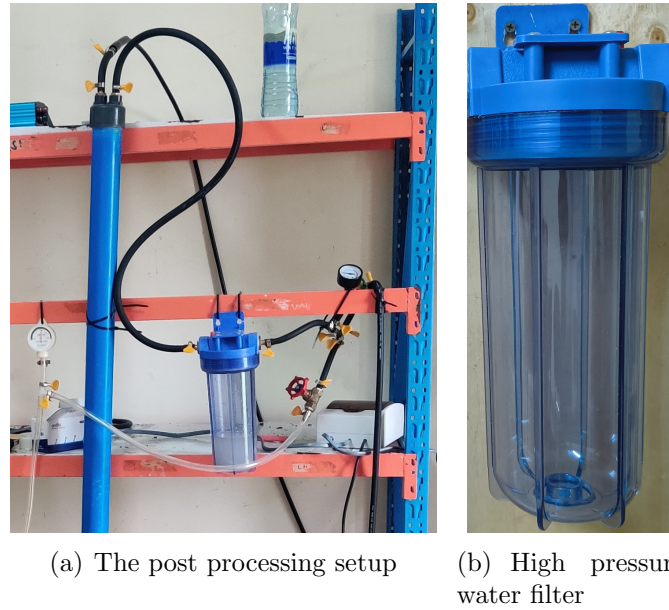


Figure 4.18: Implementation of the post processing setup

modates a different filter cartridge, a string wound cartridge. Subsequent tests showed that the replacement unit was both more reliable and more cost-effective, at TZS 18,000 compared to the TZS 30,000 required for the original preprocessing filter.

After the moisture trap, the gas stream passes through a pressure gauge (0–14 bar range) and enters a three-way splitter. One branch feeds a sampling line, permitting gas extraction and testing during operation. A brass valve immediately downstream of the splitter allows for the regulation of the flow and pressure in this sampling line. This valve requires a nipple at both sides to accommodate the LPG hose. At the high pressure side of this module, the 8 mm LPG hose is used to connect to the main output stream. At the low pressure size, the standard biogas hose was used. This sampling line is equipped with a second, low pressure pressure gauge (0–16 kPa range). The gauge allows the user to control the pressure using the valve. Later, this sampling line can be connected to the measuring equipment.

The other branch serves as the main outlet for the system. This outlet is equipped with a valve to allow easy interchange of end-users. For example, multiple tanks could be connected at the same time. For this project, a single LPG tank was connected via its own valve, enabling the system to remain pressurized while tanks are swapped.

The total cost of the post processing assembly as implemented is TZS 140,210 (EUR 46.20). This will be higher than the cost of the Kimbiji setup, which does not incorporate the ability to sample gas while the system is turned on. The total list of components is in Attachment A.4

#### 4.2.5 Power supply

Power will be supplied to both the compressor and the pump. The compressor requires approximately 110 W, while the pump is assumed to require less than 1200 W, resulting in a total power demand of maximum 1310 W. At a voltage of around 230 V, a current



of around 5.7 is thus the maximum. A safety circuit breaker rated at 6 A is chosen for protection (illustrated in Figure 4.19(a)). This one is of the MC 6K type, available in the Tronic store.

Given the reliance on solar energy in Kimbiji, accurate power measurement is essential for correctly dimensioning the energy supply. To achieve this, two energy meters, as illustrated in Figure 4.19(c), will be installed: one for the pump and one for the compressor. These energy meters, of the EM 0017-JC type, can measure energy use up to 0.01 kWh, although no accuracy was given.

For added safety, a time clock (shown in Figure 4.19(b)) was considered to automatically turn off the system after a set time, ensuring safe operation. The used model was the EM-T180, available at Tronic. However, the time clock's minimum interval of 15 minutes was deemed insufficient for full pressurization, so it was not used. The device was still left in the electrical box to allow for its utilization in further projects.

In terms of safety, three circuit breakers are included: two for switching the pump or compressor on and off, and one general breaker for overall system protection.

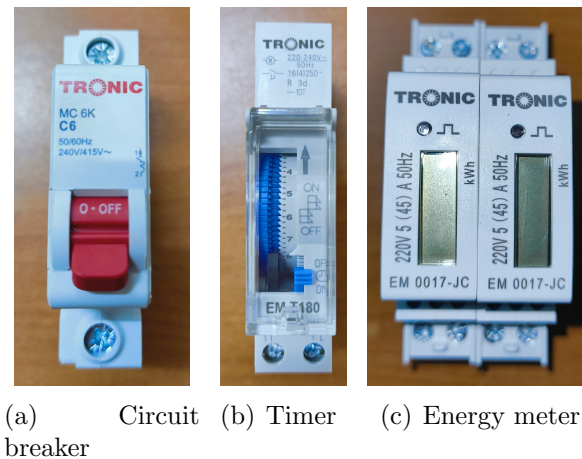


Figure 4.19: Multiple electrical parts, used in the electricity box

All of these parts were assembled into an electrical box. The electrical box was only available for purchase with pre-installed circuit breakers. The electrical box was wired using 2.5 mm<sup>2</sup> wire. External connections were made using 0.8 mm<sup>2</sup> or 2.5 mm<sup>2</sup> cable. Figure 4.20 shows the final assembly of the electrical box.

On the left is the safety breaker of 6 A, followed by the timer, two energy meters (the first for the compressor, the second for the pump), and the last two circuit breakers (the first for the compressor, the second for the pump). The pricing of all these components can be found in Attachment A.4. Since these components will not be implemented in the final Kimbiji setup and are intended solely for research purposes, the cost details are provided for reference only and are not relevant to the final system design.



Figure 4.20: Final assembly of the electrical box

#### 4.2.6 Knowledge transfer

One of the important aspects of the project is that the testing setup can be utilized and further developed by the local university. Understanding how the setup works is an important first step before further development can take place.

As a first step, the entire setup was mounted on a wooden plank, as illustrated in Figure 4.21. This makes the system compact, easily movable, and more structured. To make it intuitive for the local students, most components were labeled using a red marker.

To provide the students with operating instructions, a manual in the form of a step-by-step guide was provided. This manual focuses on four aspects of the system, printed on three sheets of paper. The complete manual is available in Attachment B. The manual was deliberately kept as concise as possible to prevent it from appearing too long or discouraging local students from reading it.

The manual is structured into four chapters. The first outlines the operation of the absorption setup, including relevant safety precautions, illustrative figures, and maintenance instructions. Chapter two addresses the water scrubbing setup, with a similar structure covering safe operation, visual guidance, and maintenance requirements. Chapter 3 provides detailed instructions for transitioning between the two systems. Chapter 4 explains the correct procedure for sampling biogas during operation.

To improve these manuals, a local undergraduate student (Mr. Elisha Yusuph Jackson) was asked to operate the system independently, without prior knowledge, using only the manual as guidance. Steps that proved unclear or difficult to execute were revised for clarity, expanded, or reformulated. This testing process enhanced the practical applicability of the documentation. Following the trial, Mr. Elisha Yusuph Jackson received a





## 4.3 Testing

To compare the performance of the upgrading systems, three sets of experiments were conducted.

The first test evaluates the  $H_2S$  removal adsorbents. Four different adsorbents were evaluated for their ability to remove hydrogen sulfide from raw biogas. The objective was to identify the most suitable material by comparing the removal efficiency and cost.

Secondly, the  $CO_2$  removal efficiency was tested. Both  $CO_2$  scrubbing techniques, water scrubbing and absorption, were tested using the same biogas feedstock to determine  $CO_2$ . The tests considered removal efficiency and processing time required to achieve the desired gas composition. In addition to this, the calorific values of the gasses were compared. The untreated biogas and LPG were tested and compared to the water scrubbing and absorption outputs. This test determines the impact of the efficiency gains in a more practical setting.

Finally, the energy usage of the compressor and the pump was measured. This was done to better design the solar energy system. In addition to this an attempt was done to measure starting current.

All pressures are given in absolute pressure, 1 bar is added to the measurements taken from the pressure gauge. The composition of the gasses is expressed in vol% and volume based ppm.

### 4.3.1 Biogas analysis

All gas measurements were performed using the IRCD4 Biogas Analyzer (Figure 4.22), which simultaneously quantifies  $CH_4$ ,  $CO_2$ ,  $H_2S$ , and  $O_2$ . According to the manufacturer, precisions are  $\pm 1\%$  for  $CH_4$  and  $CO_2$ ,  $\pm 0.1\%$  for  $O_2$ , and  $\pm 1$  ppm for  $H_2S$ .



Figure 4.22: IRCD4 biogas analyzer

To feed the analyzer, a biogas sampling pump, supplied together with the analyzer, was used. This unit pumps at a flow rate of 200 ml/min. Before gas enters the pump it passes through a dust and moisture filter to protect the analyzer, and remove the moisture from the gas.

Calibration of the analyzer proved challenging, as it requires pure gasses, which are not readily available in Tanzania. Eventually, the analyzer was partially calibrated using pure  $CO_2$  gas sourced from the Chemical Processing Engineering Laboratory, University of Dar es Salaam. This process was more time-consuming than anticipated, which limited the duration and depth of the testing phase.

However, pure  $CH_4$  was not available in this laboratory. As a result, the methane concentration was calculated, using measurements of  $CO_2$  and  $O_2$  as indicators of the gas composition. The methane volume percentage was calculated as:

$$CH_4 \text{ (vol\%)} = 100\% - CO_2 \text{ (vol\%)} - O_2 \text{ (vol\%)} \cdot \frac{100}{21} \quad (4.1)$$

This equation subtracts the measured  $CO_2$  concentration and approximately 4.76 times the measured  $O_2$  concentration (representing air, assuming atmospheric oxygen content is 21%) from 100%. This provides a reasonable estimate of methane concentration as biogas is composed primarily of  $CH_4$  and  $CO_2$ . Minor components such as  $H_2S$ ,  $H_2$ , and  $NH_3$  are not considered, as their influence is negligible.

Since the methane content is not directly measured, the accuracy of the results is uncertain and should be interpreted with caution.

### 4.3.2 $H_2S$ absorption material

The first set of tests is aimed at determining the most suitable absorption material for  $H_2S$  removal. This section begins with a description of the testing methodology, followed by the presentation of results, and concludes with a brief discussion. While the primary focus is on evaluating the  $H_2S$  removal efficiency of each material, the discussion also considers additional factors such as cost, availability, and ease of use.

#### Methodology

To compare different  $H_2S$  adsorbents, the biogas analyzer was connected directly downstream of the  $H_2S$  absorption unit, as illustrated in Figure 4.23. In this configuration, biogas flows from the digester tank into the preprocessing unit and, after leaving the absorption tank, immediately into the analyzer, without going through the rest of the system.

The analyzer's booster pump draws the gas sample continuously into the measurement cell. As the pump draws gas at a relatively low flow rate of approximately 200 ml/min, the measured adsorption efficiency may differ from that during normal system operation, where significantly higher flow rates are present. This reduced efficiency does not affect the comparative assessment of  $H_2S$  removal, since all materials were tested under identical conditions.

After system start-up, readings were taken only once the dissolved oxygen concentration reached zero, indicating that the entire flow path was purged of air and contained only biogas. Each material was tested in a cleaned absorption column. The following adsorbents were evaluated against untreated biogas:

- iron oxide (750 g, pellets),
- activated carbon (1,000 g, granular),
- steel wool (150 g, clean),
- rusted steel wool (90 g, pre-oxidized by wetting and two days of air exposure).



Figure 4.23:  $H_2S$  removal test setup

## Results

Table 4.1 shows the results of this test. In this table, the  $H_2S$  content of the biogas is presented for each of the four absorbent materials.

Table 4.1:  $H_2S$  removal efficiency of different absorbents

|                      | $H_2S$ concentration [ppm] |
|----------------------|----------------------------|
| Before removal       | 795                        |
| Granulated $Fe_2O_3$ | 3                          |
| Steel wool           | 279                        |
| Activated carbon     | 7                          |
| Rusted steel wool    | 11                         |

The granulated iron oxide showed the best removal efficiency, reaching as low as 3 ppm of  $H_2S$ . During operation, the pellets exhibited a noticeable color change and a rise in temperature. Figure 4.24 shows the change in color. This color change results from the chemical reaction taking place between the  $H_2S$  and the iron oxide.

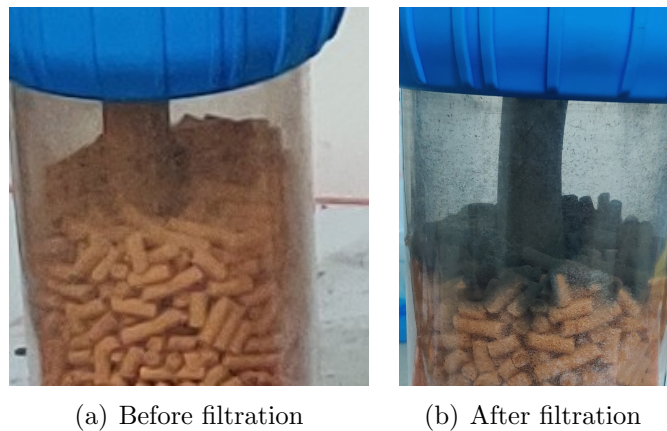


Figure 4.24: Iron oxide pellets before and after  $H_2S$  filtration

The steel wool in its original condition showed the lowest removal rate with 65% of the original  $H_2S$  removed. The remaining  $H_2S$  stays well above the targeted maximum. In

its rusted form, the removal efficiency rises significantly, with only 11 ppm remaining in the filtered gas. Activated carbon demonstrated the second-highest efficiency, lowering  $H_2S$  to 7 ppm, indicating high surface reactivity and porosity despite lacking chemical bonding mechanisms.

## Discussion

Table 4.2 provides an overview of the  $H_2S$  concentration after testing, along with the required materials and costs for one week of biogas production for each of the materials. The expected lifespan was based on calculations made in section 3.2.2, however these calculations assume 20,000 ppm  $H_2S$ , while testing showed no more than 795 ppm. The lifespan is therefore adjusted for the expected  $H_2S$  levels.

Table 4.2: Overview of various absorbent materials.

|                   | $H_2S$ concentration [ppm] | Needed amount [g] | Price [TZS] |
|-------------------|----------------------------|-------------------|-------------|
| Untreated Biogas  | 795                        | /                 | /           |
| Steel Wool        | 279                        | 40                | 1333        |
| Rusted Steel Wool | 11                         | 1333              | /           |
| Iron Oxide        | 3                          | 1.4               | 9.3         |
| Activated Carbon  | 7                          | 8                 | 280         |

Unoxidised (fresh) steel wool was tested due to its widespread availability. However, its  $H_2S$  removal efficiency was found to be unsatisfactory low. Other studies can confirm these findings [118]. The low reactivity of the steel wool made it unsuitable, since downstream equipment is sensitive to even trace amounts of  $H_2S$ . Although its able to remove 65% of the  $H_2S$ , the final concentration stay's well above the maximum permitted.

Rusted steel wool, on the contrary, emerged as a much better material. As a waste product or low-cost material, it can often be acquired in bulk at minimal expense. Although its efficiency is somewhat less predictable due to variability in rust content and compaction, it fulfills its purpose adequately when a sufficient quantity is placed in the  $H_2S$  removal unit. This test, using 90 g of it, shows that it can remove the  $H_2S$  down to 11 ppm. However, the steel wool should be sufficiently rusted. This material can be regenerated, expending its lifespan even more. Given its negligible cost, ease of sourcing, and minimal risk profile, rusted steel wool is a promising option for  $H_2S$  removal.

Granulated iron oxide showed an even higher and more consistent removal efficiency. It was able to remove 99.6% of the  $H_2S$ , leading to a final amount of 3 ppm. Its major downside is that after use the material has to be disposed of and no regeneration is possible. The operating cost for this material is low at TZS 9.3 per week. At this low cost, and with the high removal efficiency, this material also proves to be a promising option.

Finally, activated carbon has a relatively high adsorption capacity. Testing further confirmed its high absorption efficiency. It removes 99.1% of  $H_2S$ , leading to a concentration of 7 ppm. However, it presents a relatively high upfront cost. In the Tanzanian context, its price is significantly higher than that of other locally available alternatives. Moreover, once saturated, the material has to be disposed of and activated carbon must be replaced

completely with fresh, new material. Alternatively, the activated carbon can be produced locally. However, its efficiency and absorption capacity remain to be validated.

Although not tested, the removal efficiency of the absorbent materials will generally remain relatively stable throughout its lifespan, only losing significant removal capacity near saturation [131], [118].

### 4.3.3 $CO_2$ removal techniques

The  $CO_2$  removal capacity of the two used principles is tested. Absorption using  $Ca(OH)_2$  was compared to water scrubbing. This subsection also describes measurements on the calorific value of the biogas. Both from water scrubbing and Absorption. First, methodology is discussed, then, results are presented and the section is concluded with a brief discussion.

#### Methodology

Figure 4.25 illustrates the complete test setup for water scrubbing. A similar configuration was employed for the absorption setup. For each test, the entrances and exits of the columns were connected to the pre- and post processing units, respectively. The biogas initially passes through a preprocessing unit packed with rusted steel wool. After treatment, the gas is directed to the LPG storage tank. The post processing measuring valve is actively regulated throughout the experiment to maintain a constant downstream pressure of approximately 40 mbar gauge pressure to feed the biogas analyzer a constant fresh biogas stream. Maintaining a low flow rate at this stage is essential, as the outlet acts as a controlled leak point in the system. Fully opening the valve would result in high gas losses. Therefore, it must remain only partially open.



Figure 4.25: Water scrubbing and absorption test setups

As a first step, the composition of the untreated input biogas was measured. After this step, the system and biogas tank were flushed to remove the air and replace it with biogas. The system was flushed until the oxygen concentration dropped to 0 vol%. The tank was initially filled with air. Biogas was then pumped into the tank until a pressure of 4 bar

was reached, after which it was released back out. This process was repeated until the oxygen concentration dropped below 1 vol%.

Before testing the absorption setup, the  $Ca(OH)_2$  inside the column was replaced with 150 g of new material. This ensures that the material will not be depleted during the course of the test. Once the material was added, the test commenced. The experiment begins at 1 bar and continues until the pressure reaches 8 bar. The analyzer records the concentration every 6 seconds and transmits the data to a laptop. Regular pressure readings were also taken.

After these tests were performed, the LPG tank was filled with biogas. In a final test, the calorific value of the end product of the 2 filtration systems is compared and evaluated against each other. In addition to this, the calorific value was compared against the untreated biogas and against LPG.

The  $CO_2$  removal efficiency can be calculated by dividing the amount of  $CO_2$  removed from the biogas by the total amount of  $CO_2$  originally present. This formula assumes that air or  $CH_4$  are unable to enter or exit the system. The removal efficiency can be calculated using the measured gas input and output, this correlation is given in Equation 4.2.

$$\text{Removal Efficiency} = \frac{[CO_2]_{\text{Initial}} - [CO_2]_{\text{Final}} \cdot \frac{[CH_4]_{\text{Initial}}}{[CH_4]_{\text{Final}}}}{[CO_2]_{\text{Initial}}} \times 100\% \quad (4.2)$$

During the process, the total volume decreases as  $CO_2$  is filtered out. Equation 4.2 takes into account this volume reduction and represents the relative reduction in  $CO_2$  concentration, by assuming no  $CH_4$  is able to enter or exit the system.

For this test, the biogas was released from the LPG tank using a reducer. This reducer maintains a constant output pressure of 30 mbar. After this, the gas is combusted in a biogas stove to heat 500 ml of water in a small pot. Figure 4.26 shows the test setup.



Figure 4.26: Calorific value test setup

Temperature was recorded using an alcohol thermometer calibrated over a span of  $-10\text{ }^{\circ}\text{C}$  to  $+110\text{ }^{\circ}\text{C}$ , with an instrumental uncertainty of  $\pm 1\text{ }^{\circ}\text{C}$ .

To measure the calorific value of biogas, the Wobbe Index can be used [132]. For reference, ISO 15971:2008 is the standard that defines this testing protocol [133]. This test requires gas flow to be measured, this is unavailable in the rural setting of this project. Instead, power can be determined by using the formula that calculates heat power from the change in temperature.

In order to determine the energy content of the biogas, a fixed volume of water was heated to boiling on a stove adjusted to its highest setting. The time required to achieve boiling was measured, and the calorific value was then derived using Equation 4.3.

$$P = \frac{\Delta T \cdot m \cdot C_v}{t} \quad (4.3)$$

In this formula, the useful power  $P$  is calculated using the temperature difference  $\Delta T$  between two measuring points, in this case between 40 °C and 90 °C. The fluid used in this case is water with a mass  $m$  of 500 g and a specific heat capacity  $C_v$  of 4.184 J/g°C. The time  $t$  is the variable, and is measured in each of the tests.

## Results

To understand the effects of the different processing options, first, the initial biogas concentration was measured. Table 4.3 shows the concentration of untreated biogas.

Table 4.3: Initial gas composition

| Substance | Concentration [vol%] |
|-----------|----------------------|
| $CH_4$    | 64                   |
| $CO_2$    | 35                   |
| $O_2$     | 0.5                  |
| $H_2S$    | 705 ppm              |

The unfiltered biogas contains approximately 35 vol%  $CO_2$ . The  $CH_4$  content is 64 vol%. This is well below the target concentration for cooking or heating. In addition to these two main gasses,  $O_2$  and  $H_2S$  were also present. The presence of  $O_2$  indicates a leak.

The presence of  $O_2$  also indicates the presence of  $N_2$ , since the amount of  $N_2$  was not measured, this should be taken into account in the interpretation of the results. The concentrations of  $CO_2$  and  $CH_4$  would be higher without leak.

During the test, when the compressor was running,  $O_2$  leaked into the system in significant amounts. Figure 4.27 illustrates oxygen concentrations during the process, in relation to pressure.

In the absorption system, the concentration of  $O_2$  begins at 8 vol%, then drops and stabilizes at approximately 3 vol%. This means that a significant portion, around 15 vol% of the gas mixture is residual air. The elevated  $O_2$  concentration at low pressures is attributed to air left in the sampling line when the system was first activated.

In the water scrubbing system, the  $O_2$  concentration does not see an initial spike. The  $O_2$  concentration is slightly higher than the absorption system at around 4 vol%.



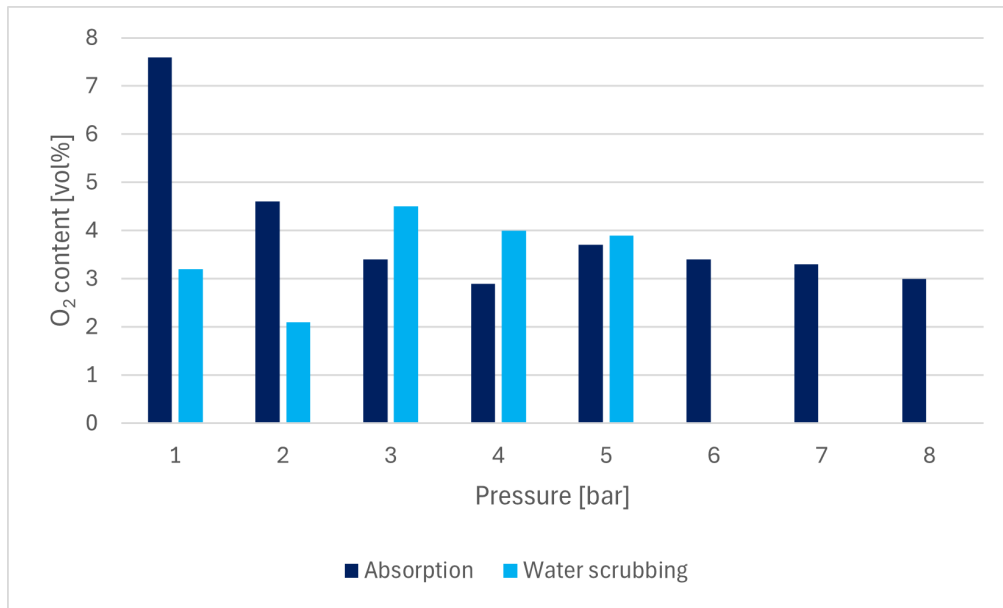


Figure 4.27:  $O_2$  content in relation to the output pressure, for the water scrubbing and absorption purification systems

To compare the  $CO_2$  concentration after purification with the initial values, the  $CO_2$  concentrations were rescaled. This rescaling assumes that the combined concentration of methane and  $CO_2$  equals 100%. Figure 4.28 illustrates the results of the purification techniques.

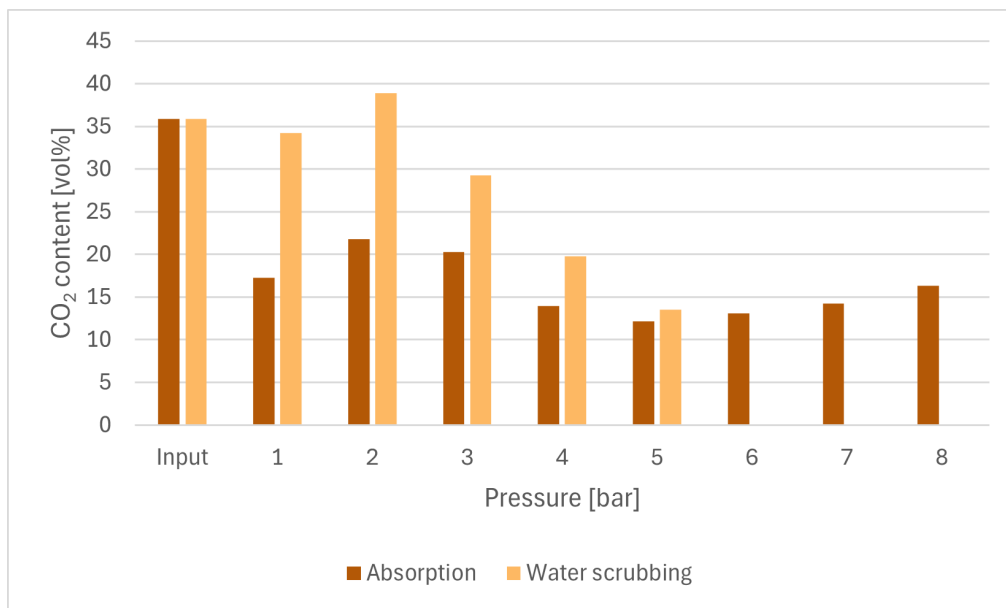


Figure 4.28:  $CO_2$  content in relation to output pressure using the absorption and water scrubbing setup

When testing the absorption setup, the  $CO_2$  concentration fluctuates between 13 vol% and 20 vol%. Initially, it remains stable at around 20 vol%, after which it drops and slowly increases to reach 16 vol%  $CO_2$  at 8 bar. This reduction represents adequate reduction from the original concentration of 35%.

For water scrubbing, at low pressures, the filtered gas composition closely matched the



input biogas feed ( $CO_2$  approximately 34 vol%,  $CH_4$  approximately 66 vol%). As the pressure increased to 4 bar,  $CO_2$  removal proceeded steadily:  $CO_2$  content decreased from 34% to 14%. If the system was able to reach higher pressures the  $CO_2$  content was likely to drop further.

Above 5 bar, the system reached its hydraulic limit. At approximately 5 bar the water pump stalled, no further water could be circulated, and scrubbing ceased. This behavior was consistently reproduced in a second trial, confirming that the pressure washer pump lacks the required head capacity for pressures above 4 bar.

At the highest achievable pressures, the water scrubber achieved a removal efficiency of almost 60%  $CO_2$  under stable operation. When the water scrubbing setup was switched on, the pump generated elevated noise levels.

Next, the calorific value of the two gasses is determined. Table 4.4 illustrates the estimated power, using Equation 4.3, and heating time. The untreated biogas measurement was only carried out between 40 °C and 80 °C as the digester was empty at approximately 85 °C. The increase in LPG temperature was also measured between 40 °C and 80 °C. This difference from water scrubbing and absorption (between 40 °C and 90°C) has an influence on the required time, but not on the power.

Table 4.4: Calorific value test results

|                  | Time (s) | P (W) |
|------------------|----------|-------|
| Untreated biogas | 985      | 79    |
| Water scrubbing  | 325      | 322   |
| Absorption       | 390      | 268   |
| LPG              | 363      | 230   |

The results indicate that the biogas treated by water scrubbing yielded the highest energy content, with an estimated power of 322 W. Gas treated through the absorption process produced slightly less energy, achieving approximately 83% of the power output of water-scrubbed gas. Both treated gasses performed significantly better than the untreated biogas. LPG delivers 230 W of power in this test, this is far below what absorption and water scrubbing were able to achieve.

During testing, the biogas produced a clear flame with a distinct blue base, making it difficult to see. The flame from untreated biogas displayed a slightly deeper blue hue. The invisible flame from purified biogas poses a significant hazard, as it is challenging to discern whether the gas is combusting or not.

## Discussion

As an initial observation, there was proximately 3 vol%  $O_2$  in the system. This is likely caused by a leak in the biogas tap on the digester. The tap was damaged and sometimes leaked. When the compressor draws biogas from the supply hose, the resulting negative pressure can cause air to flow in through the damaged tap, introducing it into the system.

During operation, the water scrubbing setup had a sudden spike of  $CO_2$ . This spike is because the water level inside the scrubbing column shortly exceeded the maximum water level, pulling water through the exit hose into the high pressure moisture trap. This locally

expanded the water and decreased the pressure, releasing  $CO_2$  back into the gas stream. After this spike, as the pressure continued to increase, the efficiency increased as well.

The removal efficiency of the water scrubbing increased significantly as the pressure increased during the test, achieving an average removal efficiency of 32%, while reaching removal of 70% at 5 bar. The high pressure is thus crucial for efficiency. If a consistent high efficiency is wanted, a pressure relief valve that keeps the pressure sufficiently high should be incorporated into the design to keep removal efficiency high throughout the process.

In contrast, the absorption setup reached significantly higher pressures and delivered a more consistent gas output. With an average  $CO_2$  removal efficiency of 68%, this setup performs better than water scrubbing. However, the removal efficiency at 8 bar of the absorption process was 68%, compared to 70% for the water scrubbing process, indicating water scrubbing would be a better option when the setup can be kept at high pressure. The  $CH_4$  percentage would average on 84%, if no leak was present. This setup meets the criteria of 75%  $CH_4$ .

The calorific value test illustrated that both purification options were able to significantly improve the power of the gas compared to unpurified biogas and LPG. The higher efficiency of water scrubbing results in a 17% higher power than absorption. This is not explainable by using  $CH_4$  percentage, as average  $CH_4$  percentage would be higher for absorption. The difference can only be explained by factors such as wind, flame physics and thermometer inaccuracy. If this were further analyzed in the future, the tests should be done in a more controlled environment.

However, the absorption system is not without drawbacks. Its primary disadvantage is the need for periodic replacement of the absorbent material. This results in additional operational costs and requires user intervention approximately once a week, depending on gas production rates. Although the column is equipped with a system to facilitate the replacement of the absorbent, this process has been found to require significant manual force.

Given these factors, absorption is the more suitable technique for this application. It offers a substantial reduction in power consumption, lower operational costs, and only a marginal decrease in  $CO_2$  removal efficiency.

#### 4.3.4 Energy measurements

To determine the appropriate size of the solar energy supply required for the system in Kimbiji, the energy consumption of the main electrical components in this setup are measured. In the absorption setup, only the compressor consumes power, whereas the water scrubbing configuration requires both a compressor and a circulation pump, resulting in higher total energy demand.

##### Methodology

The energy use was measured during the compression of biogas to 8 bar into the LPG tank, thereby simulating a typical operational cycle. The time was measured and the energy was recorded with the energy meters (as seen in Figure 4.19(c)) installed. This

allows the calculation of the power  $P$  and total energy used. The test was repeated multiple times to achieve more accurate results.

In addition to measurements to determine  $P$ , a measurement was done to calculate the power factor ( $\cos \phi$ ). Apparent power can be calculated as shown in equation 4.4. This would require the measurement of voltage  $U$  and current  $I$ .

$$\cos \phi = \frac{P}{U \cdot I} \quad (4.4)$$

These measurements were taken using the DT9205A digital multimeter. The multimeter is shown in Figure 4.29. According to the manufacturer, the device has an accuracy of  $2\% + 0.1$  A when measuring current, and an accuracy  $1.2\% + 5$  V when measuring voltage.

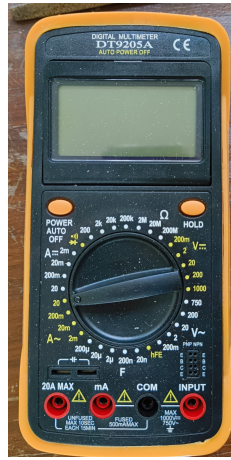


Figure 4.29: Multimeter DT9205A

The inrush current of both the compressor and the pump was measured multiple times using the digital multimeter. However, due to the short duration and dynamic nature of inrush currents, these measurements are not accurate. Capturing accurate inrush behavior would require a more specialized instrument, such as an oscilloscope.

## Results

The first test, using the energy meters, showed an average time span of 10.3 minutes. The average energy used by the compressor was 16.7 Wh. This translates to 97 W of active power. The pressure washer was not tested enough to take adequate measurements using the energy meter.

Voltage was consistently measured at 220 V throughout all tests. The compressor exhibited a nominal operating current of 0.6 A, while the pump consumed 2.6 A regardless of system pressure.

Using Equation 4.4, the power factor can be determined. For the compressor, a power factor of 0.73 was calculated. This should be taken into account when sizing the inverter.

Since no measurement was taken of the pressure washer pump, the actual power of the pump can be calculated another way, assuming the power factors of both motors are equals. Using equation 4.4, the actual power can be estimated at 418 W. While this value is not exact, it provides a reasonable approximation.

Measured inrush currents were 2.35 A for the compressor and 4.56 A for the pump. These values were obtained using a digital multimeter and should be interpreted with caution due to the transient nature of inrush currents.

## Discussion

Regarding energy use, the water scrubbing system requires a total of 515 W, compared to just 97 W for the compressor used in the absorption setup. Furthermore, from a user experience perspective, the pump produced a high noise level during operation. This noise was sufficient to hinder verbal communication throughout the testing. In a rural context, such disturbance is undesirable and could reduce community acceptance of the technology.

Measured inrush currents yielded ratios of approximately 2:1 for the water pump and 4:1 for the compressor relative to their respective nominal currents. However, owing to the lack of specialized instrumentation, these values are likely underestimated and should be treated with caution.

These results indicate that, in the present configuration, the absorption-based treatment outperforms the water scrubbing system. However, in section 4.1.3, a booster pump alternative was discussed. This pump was capable of delivering the same outlet pressure at reduced flow rates and with lower power consumption. It could be substituted into the water scrubbing process. If such a pump is adopted, the water scrubbing system would satisfy the energy efficiency requirements.

## 4.4 Optimization recommendations for the Kimbiji setup

The design and operation of the biogas system in Kimbiji should align with the principles of sustainability, cost-efficiency, and local applicability. In particular, emphasis should be placed on transforming waste into value. To ensure economic feasibility in a rural context, all system components and operational procedures should be kept as simple and low-cost as possible, without compromising functionality.

The university setup gives a first indication of the price of the full setup. The total price, excluding the cost of energy is TZS 488,540 (EUR 160.98) for the absorption setup and TZS 683,300 (EUR 225.16) for the water scrubbing setup.

### 4.4.1 Purification

Although both iron oxide and rusted steel wire proved to be effective absorption materials for  $H_2S$  removal, rusted steel wire was selected for implementation in Kimbiji. The material aligns well with the site's philosophy of turning waste into resources, as it can be locally sourced from scrap iron. This approach not only reduces costs but also enhances the sustainability of the system.

However, rusted steel wool did not reach the required minimum outlet concentration of 5 ppm  $H_2S$ . The amount of absorbent should be increased to improve the removal effi-

ciency. While test results did not consistently meet this target concentration, the approach is deemed acceptable given the ease of implementation and local material availability.

If performance proves insufficient during testing, an alternative absorption stage using granular iron oxide should be used. This material offers higher removal efficiency but introduces an operational cost estimated at TZS 9.3 per week, and would need to be sourced externally. Although the cost is low, the spent absorbent presents a fire hazard, making its use undesirable.

For  $CO_2$  removal, the absorption principle will be employed, this technique is capable of reducing the  $CO_2$  concentration to 14%, it is suitable for the context of Kimbiji. Since  $Ca(OH)_2$  proved to have a good efficiency, it will be used again in Kimbiji. The lower section of the column should be extended to increase the amount of  $Ca(OH)_2$  that can be refilled at a time.

During university testing, refilling the absorption column proved difficult, as it required turning the column upside down. To avoid similar challenges in Kimbiji, a design modification is proposed: integrating a refill port with a glued PVC threaded female socket at the top endcap of the column. This simple improvement will allow water replenishment without disassembly, reducing maintenance effort and improving usability in the rural context.

#### 4.4.2 Compression

The biogas digester in Kimbiji is projected produce 100 L of biogas per day, substantially higher than the university digester. To ensure that the increased gas throughput can be processed within acceptable time, the total cycle duration can be calculated. This will determine whether the existing compressor can meet the amplified demand or if higher capacity is required.

In the absence of direct flow measurements, the gas volume was estimated from the amount of LPG in the LPG cylinder, which is 6 kg [134]. Using a density of 0.55 kg/L, this translates to a volume of approximately 11 L. This assumes a fill ratio of 100%. Adopting this volume and assuming ideal-gas behavior at 1 bar and 30 °C, the biogas composition was adjusted to reflect the removal of 21 vol%  $CO_2$  and 784 ppm  $H_2S$ . The purified stream is subsequently compressed to 8 bar to occupy the 11 L vessel. Under these controlled conditions, the intake of raw biogas at ambient pressure and temperature is calculated to be approximately 112 L. Although derived under idealized assumptions, this estimate is sufficient for planning cycle times. Given an average daily biogas production of 100 L, and some losses, slightly more than one tank can be filled per day.

A single cycle of purification and compression is capable of processing almost the entire biogas production of one day in only 10.6 minutes of operation. Consequently, the compressor remains inactive for over 99% of the time, meaning the compressor is too large for the current throughput. On the contrary, this means the compressor will have a longer lifespan and a minimal chance of thermal overload.

Since the absorption setup will be implemented, and no pump is required, the power consumption will only be 97 W, with a power factor of 0.73. The starting current of the

compressor was measured at 2.35 A, this should be taken into account when the solar system for Kimbiji is designed.



# Chapter 5

## Kimbiji setup

The Kimbiji installation builds upon the insights and outcomes from the university test setup, but introduces new constraints related to its rural context. Limited access to specialized tools, no electricity grid, and the need for simple maintenance procedures all influenced the design philosophy. As a result, the system prioritizes robustness, ease of use, and cost-effectiveness. Moreover, since the setup will be operated by local students and community members, user-friendliness and durability were key design drivers for this setup.

The chapter commences with a thorough examination of the selection of components, providing a thorough explanation of the function of each component, the reasons behind its utilization, and its significance within the greater context of the entire system. For purification and compression, this section discusses the differences between the setup at the university and the one in Kimbiji. Finally, this section discusses the component selection of the energy supply.

The subsequent section delves into the implementation process, elaborating on how the chosen components are integrated and interconnected within the system. Emphasis is placed on establishing a configuration that is both educationally beneficial and safe to use. This is particularly critical, given that the power supply is responsible for managing high currents within the system. This chapter primarily concentrates on energy supply, a part not previously incorporated in the university's configuration. Effective knowledge transfer is crucial at this location, as students and community members will operate the system.

The third section is dedicated to validating this setup. Initially, it examines the purification efficiency to verify that the system achieves the objectives. Following this, the section evaluates the power supply, confirming that it provides a steady and adequate energy supply.

Following this, the subsequent chapter delves into the weaknesses present in the design and proposes solutions for these shortcomings. Additionally, this section will outline the necessary actions required for the system's upkeep.

The final chapter will outline a full scale setup aimed at accommodating the initial Kimbiji design's production capacity of 6,500 L per day. It will introduce a concept, explore the



necessary modifications to various components, and provide a detailed estimation of the total costs involved in implementing this setup.

## 5.1 Component selection

This section outlines the rationale behind the selection of components for the Kimbiji installation. Where feasible, components of the university prototype were adopted in full. When such parts were unavailable or unsuitable, suitable alternatives were sourced. For the deployment of this setup, reliability, maintainability, cost-effectiveness and overall robustness served as the primary selection criteria.

Similarly to the university system, most components were purchased from the Kariakoo market. However, due to time constraints, all elements of energy supply, including solar panels, a controller, an inverter and a battery were purchased from a single specialized solar equipment retailer in Kariakoo. This was not ideal, as purchasing them from smaller local stores would result in more cost-efficient alternatives.

### 5.1.1 Purification and compression setup

The complete absorption and compression system originally developed and validated in the university setup proved reliable and robust. For the Kimbiji deployment, the majority of the components, including PVC pipes, valves, pressure gauges, and the compression unit, remained unchanged. By matching the university setup, the behavior of these components is predictable, since they were tested in the first setup.

One notable modification focuses on the  $H_2S$  removal stage. In place of the ungrooved polypropylene (PP) fiber cartridge employed in the university system. This setup uses a string-wound cartridge filter of an identical nominal rating of 125 PSI (approximately 8.6 bar), as used in the post processing stage of the university setup. It proved more reliable at high pressures. At a purchase price of TZS 18,000, TZS 12,000 lower than the original PP cartridge, this substitute achieves equivalent removal efficiency while reducing the total cost of the system. Figure 5.1 illustrates the original and substitute water filters.



(a) Original water filter (b) Substitute water filter

Figure 5.1:  $H_2S$  removal unit

For the absorption material, rusted steel wool was chosen. This material proved to be the most promising option. Ten 15 g packets (150 g total) were fully saturated with water and allowed to rust under ambient conditions for 48 hours, producing an extensive  $Fe_2O_3$  layer rich in rust. More rust translates to a higher removal efficiency. This material can be regenerated or replaced after each cycle to maintain consistent removal capacity. The cost of the steel wool was TZS 5,000.

Alternatively, in the future, other rusted steel alternatives, such as scrap steel, can be used for this purpose. For this scrap steel, it is important that the steel surface is as large as possible to optimize the interaction between  $H_2S$  and the steel. Ideally for this purpose are very small pieces of metal, such as turnings or milling swarfs. Secondly, the steel should be as rusted as possible in this reaction. Before full-scale implementation, these materials must be validated for their  $H_2S$ -removal capacity and overall efficiency. An additional advantage is that this approach turns what would otherwise be a waste product into a valuable, sustainable treatment medium.

The compression unit remains unchanged from the university design, processing 112 L of biogas in 10.6 minutes (approximately 614 L/h). If demand increases, the system can operate for longer periods, provided there is sufficient sunlight.

To store the biogas, the same 15.6 kg tank cylinder (see Figure 4.10(b)) was selected. The daily gas production in Kimbiji is 100 L, to fill one of these tanks, 112 L of raw biogas was needed. This size thus requires slightly more gas than the current daily production at the Kimbiji site. The system would be able to fill slightly more than 6 of these tanks every week.

### 5.1.2 Energy Supply

The energy supply system for the Kimbiji installation includes solar panels, a lead-acid battery, a PWM controller, and an inverter. All components were selected based on availability, cost-effectiveness, and performance within the expected energy demands of the system.

For this system, the compressor is the only power user, and it has a measured average power consumption of approximately 97 W. In addition, household lighting and other small-scale loads are expected to require 200 W, leading to a total system demand of around 297 W.

#### Solar Panels

For electricity production, monocrystalline solar panels rated at 200 Wp were the most cost-effective option in this specific store. Two panels were selected, providing a combined output of 400 Wp. Having this capacity ensures sufficient power can be delivered to the system, even after losses are taken into account. Each panel was purchased at TZS 250,000. Figure 5.2 shows the solar panels mounted on the roof.



Figure 5.2: Selected solar panels

## Battery

To support the compressor's high inrush current during startup and to provide power for nighttime lighting, a sealed lead-acid battery was selected. The smallest available solar battery from local vendors had a capacity of 50 Ah, which exceeds the system's estimated requirements. This battery was purchased for TZS 170,000. Although a standard automotive battery would have been a more economical choice, the limited timeframe of the project required the use of an off-the-shelf solar battery. Figure 5.3 shows the selected unit, a 12 V sealed lead acid battery. Compared to conventional car batteries, this type typically offers a significantly longer service life [135], [136]. However, it is less suitable for handling sudden current surges. Because the solar panels will be connected during system operation, this limitation may not pose a problem. The system's behavior under real operating conditions will need to be verified during the validation phase.



Figure 5.3: Selected battery

The limited capacity of the battery will only support the site's lighting for a short period of around 1.5 hours. However, if the power needed for the lights stays limited, this duration can be extended. In the future, if needed, an additional battery can be placed in parallel to the existing one for additional capacity.

## Controller and inverter

The solar array produces 400 Wp, but the energy system was sized for 600 W to accommodate a potential third panel in future upgrades. A hybrid inverter (combining PWM

controller and inverter functionality) rated at 600 W was available for TZS 560,000. However, selecting separate components proved more cost-effective.

A standalone 600 W inverter was acquired for TZS 80,000. To support an output of 600 W at 12 V, a current rating of approximately 50 A was required. A 60 A PWM charge controller was selected and purchased for TZS 130,000. Although an MPPT controller was available for TZS 608,000, it was not chosen due to its relatively limited power gain at lower power levels, if in the future the energy supply gets significantly upgraded, an MPPT controller might be more cost effective. The selected inverter and controller are shown in Figure 5.4.



Figure 5.4: Selected inverter and PWM controller

## 5.2 Implementation

This section discusses the implementation of the setup at the Kimbiji site. Similarly to the university installation, the experimental setup, except for the photovoltaic array, was mounted on a single wooden plank illustrated in Figure 5.5(b). To protect against moisture ingress and UV radiation, the plank was varnished before mounting the components. The plank was securely mounted on a wall next to the existing biogas processing setup. Figure 5.5(a) illustrates the full setup.

At the Kimbiji site, a small building was constructed. From this structure, a canopy extends over a patio under which the purification setup is positioned. This canopy provides protection against direct rain, thus prolonging the lifespan of the system. Placing the system directly under this roof also minimized the required cable length to connect the system to the solar panels.

### 5.2.1 Purification and compression setup

Most of the implementation concerning purification and compression aligns with what was done at the university setup. This subsection elaborates on each component and details its placement and maintenance procedures. To operate this setup, a manual was also provided. This manual is provided in Attachment E.

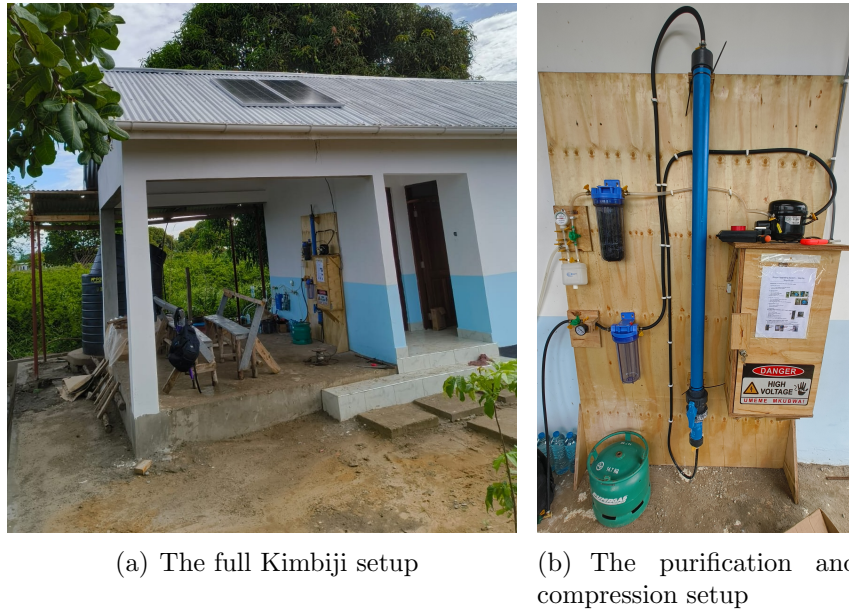


Figure 5.5: The Kimbiji setup

### Placement and connection to the digester

To integrate the scrubbing and compressing train of this project with the existing biogas testing rig, the digester outlet line is tapped immediately upstream of the current system as shown in Figure 5.6. The existing system, which evaluates how different feedstock blends affect biogas quality, draws gas from the 3,000 L digester, then passes it sequentially through a dehumidifier, a  $H_2S$  scrubber and a flow meter before exiting through a biogas valve.

A T-fitting is installed immediately after the digester outlet, allowing the gas to flow to both systems. In practice, both branches remain permanently connected. Switching between them only requires minor valve adjustments. This arrangement ensures continuous access to the digester gas for both setups.



Figure 5.6: Connection between digester outlet and dual-branch test setups

In operation, raw biogas enters the assembly from the left. At the junction, the lower branch leads to the original testing rig, where weekly performance metrics are recorded, while the upper branch delivers gas to the newly developed scrubber and compressor sequence.



In contrast to the garden hose at the university facility, this setup employs a standard flexible biogas hose as the supply line between the existing setup and this project's setup. This hose is securely mounted to the wall to prevent mechanical damage. Alternatively, the system can be fed from the other digester located at the site. However, this would require the hose to traverse 10 m of rough, uneven terrain. In this case, using a water hose similar to the one employed at the university may be more suitable.

## Preprocessing

The implementation of the preprocessing unit remained largely similar to that of the university setup. The water filter was modified in a manner similar to the university setup. A short section of garden hose was glued to the inside of the filter to force the gas through the entire filter before exiting, increasing contact time with the absorbent. This is done similarly to the  $H_2S$  filter in the university setup (Figure 4.13). The Kimbiji preprocessing setup is shown in Figure 5.7.

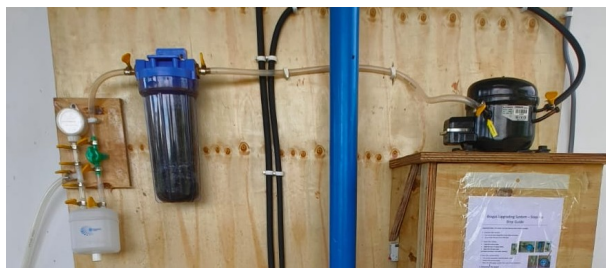


Figure 5.7: Preprocessing setup at the Kimbiji setup

At this setup,  $H_2S$  removal employs rusted steel wool as the absorbent. 10 steel wool packages of 15 g each were fully saturated in water and left to oxidize for 48 h, forming an extensive  $Fe_2O_3$  layer that chemisorbs  $H_2S$ . By having more rusted steel wool packets in this setup, the project aims to achieve higher removal efficiencies. After saturation, the material can be regenerated on-site by exposing it to open air for 24 to 48 hours, allowing partial re-oxidation, restoring its absorption capacity. The manual suggests regular regeneration every two weeks to maintain consistent performance.

## Absorption column

The absorption column itself has the same design as the university column. The only modification lies in the geometry of the endcaps. Figures 5.8(a) and 5.8(b) compare the original and redesigned endcaps, respectively. The new PVC threaded female socket has a nominal diameter one size smaller, allowing the installation of two fittings side by side (Figure 5.8(c)). This arrangement increases system flexibility. By drilling an additional port into the endcap and adding another PVC threaded female socket, the unit can be easily converted to a water scrubber setup.

A second modification to the implementation of this setup is the length of the absorption column. The bottom part was elongated to allow more  $Ca(OH)_2$  to be added to the column. The full length of the bottom part is 20 cm. Together with the upper section, the total column height is 186 cm.

This system will use the same  $Ca(OH)_2$  as the university setup. Per day, 100 g of  $Ca(OH)_2$  will be consumed per day, as calculated in 3.4.1. The bottom of the absorp-



(a) University implementation (b) Kimbiji implementation (c) Proposed dual exit endcap

Figure 5.8: Different implementations of endcap design

tion column is designed to hold the maximum required absorbent for a week of biogas production, or about 700 g of material. Because  $CO_2$  only partially dissolves, the actual required amount would be lower. This will be verified during validation. When using this setup, waste will be generated in the form of  $CaCO_3$ . This  $CaCO_3$  can be distributed or sold locally for use with fertilizers to improve soil quality.

### Post processing

Finally, the post-scrubbing stage has been significantly simplified. The dedicated gas sampling line present in the original configuration has been eliminated, as there is no need for constant quality control in this setup. Gas exiting the absorption column passes through a moisture trap and is then directed to the output, an LPG tank in this case. If in the future more gas has to be processed, this output stage can be redesigned to accommodate multiple tanks simultaneously.

### Gas usage

When biogas has to be extracted from the LPG tank, a reducer is used. This reducer, as illustrated in Figure 5.9, reduces the biogas pressure to 30 mbar. At this pressure, the biogas can be used on a gas stove. These reducers are rated for maximum overpressures of up to 7.5 bar.



Figure 5.9: Standard LPG reducer

## Overview

The complete purification and compression setup is illustrated in Figure 5.5(b). The total price for this system is TZS 432,720 (EUR 142.59). Operating costs for the  $\text{Ca}(\text{OH})_2$  and biogas tanks are not included in this amount. The  $\text{Ca}(\text{OH})_2$  must be replaced every 700 L and costs TZS 980 (EUR 0.32) per 700 L. The LPG tanks required to store the biogas cost TZS 20,000 (EUR 6.59) each, but they can be reused indefinitely. A complete description of the components is given in the Attachment D.1.

### 5.2.2 Energy Supply

This subsection will discuss the implementation of the energy supply. Since the supply will be placed in a rural area and locals with little knowledge of electricity will have access to it, safety will be key.

The energy supply system is housed within an electrical box. This box serves to protect and organize all critical components involved in the harnessing of solar energy. To minimize project costs and due to the availability of spare wood, the decision was made to construct the box from scratch rather than purchasing a pre-fabricated enclosure, this proved to be more cost-effective.

#### Solar Panel Installation

The solar panels could have been mounted on the ground or on a rooftop. By placing the panels on the roof of the building, they are placed with an incline, allowing water to glide off with ease. Another advantage of placing the solar panels on the roof is that it protects them and the connections from physical damage and theft. However, this configuration also makes routine cleaning and maintenance more labor intensive. The installed solar panels are shown in Figure 5.10.



Figure 5.10: Solar panels mounted on roof

The solar panels were mounted directly onto the corrugated roof sheets using nails. Two small holes were drilled to guide the cables through. On the underside of the roof, the panels were wired in parallel to each other and connected with a  $4\text{ mm}^2$  cable. This cable, with a length of 3 m, then connects directly to the PWM controller.

#### Internal Configuration

The electrical box was installed at an easily accessible height. The box houses the battery, PWM controller, inverter, and one DIN rail with terminal blocks. The layout was kept



compact and logical for straightforward maintenance and troubleshooting. Figure 5.11 shows the completed configuration. A slight gap was left between the wooden board and the sideboards of the box, permitting some ventilation in the box to prolong battery lifespan.

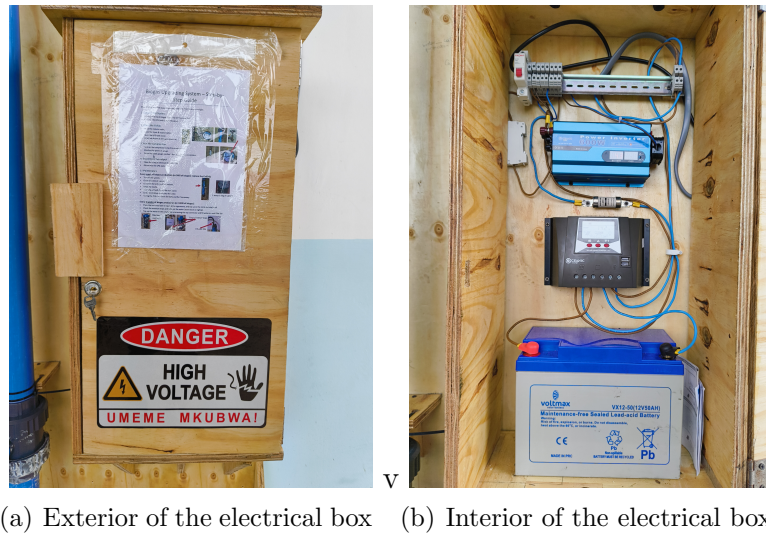


Figure 5.11: The electrical box at the Kimbiji setup

The DIN-rail inside the box holds several terminal blocks used for electrical connections to simplify maintenance. The main switch for the system is a 6 A circuit breaker, serving as the main control switch towards the compressor. The installation is shown in Figure 5.12. This breaker can be operated from the outside of the electrical box.



Figure 5.12: Circuit breaker used as main switch

To support future expansions such as lighting or additional low-power components, additional terminal blocks and a secondary circuit breaker have been installed. They are currently installed but not yet connected.

## Overview

The total cost for the energy supply components, including cables, was TZS 953,750 (EUR 314.27). This number is relatively high compared to other system components, particularly the gas purification setup. However, the chosen components were deliberately oversized to ensure reliability and future flexibility.

Purchases were made under time constraints. Nevertheless, during the procurement process, equivalent components were found in other shops at prices more than 30% lower. This observation should be considered in future implementations to further optimize budget allocation.

### 5.2.3 Maintenance and manual

For this setup, a manual in the form of a step-by-step guide was also provided (see Attachment E) to assist locals who wish to use the system. This manual explains how to operate the system and outlines the most important maintenance steps. It outlines the replacement procedure for the absorbents used (the rusted steel wool and  $\text{Ca}(\text{OH})_2$ ), the emptying of the moisture traps, and how to check the water level in the absorption column. The videos produced at the university setup can also be used for this setup?.

A small box containing tools, replacement materials, and spare parts was left with the setup to improve the usability of the system. The tools include an English key, a tool to securely open and close the water filter, a lighter and a toolbox to repair the system if it gets damaged. The english key can be used to unscrew the top brass nipple, allowing the column to be filled to the appropriate water level.

For the  $\text{Ca}(\text{OH})_2$  replacement step, approximately 10 kg of  $\text{Ca}(\text{OH})_2$  were also left at the site, allowing the system to run without operating cost for the first 14 weeks or 3 months of purification. Each refill requires 700 g of the absorbent. To estimate this amount, an unused endcap can be used as a measuring aid. This endcap, as illustrated in Figure 5.13, can hold 50 g of  $\text{Ca}(\text{OH})_2$ . This is a simple and robust way to estimate the replacement material.

Given the rural context in which the system will be deployed, where local residents are likely to have limited knowledge of electrical systems, additional safety precautions were implemented. The electrical box is equipped with a mechanical lock, with only two keys available. These will be provided only to individuals with sufficient knowledge of electrical safety. In addition, a clearly visible warning label has been placed in the box to warn of electrical hazards and discourage unauthorized access.

Only skilled professionals familiar with electrical systems should perform maintenance tasks. The manuals for the inverter and the controller are placed inside the electrical box to assist in maintenance.



Figure 5.13: Unused endcap holding 50 g of  $Ca(OH)_2$

## 5.3 Testing

This section discusses the validation of the Kimbiji setup. It outlines key performance indicators and compares the Kimbiji condition to those at the university setup to ensure operational reliability and effectiveness.

The first validation step is to assess biogas quality. Here, the  $H_2S$  absorbent will be evaluated to ensure sufficiently high removal efficiency. The second validation step focuses on the  $CO_2$  concentration. These tests must verify that the concentrations are reduced to acceptable levels for safe and efficient combustion performance in end-use applications.

Subsequently, the calorific value of the gas will be estimated and compared against the results from the university setup and LPG. This comparison is used to assess whether the gas meets the required quality for cooking.

In the final subsection, the energy supply will be evaluated. Here, the effects of nominal current and peak inrush currents will be discussed. In addition, the maximum yield for the solar panels will be estimated.

### 5.3.1 Biogas quality

This subsection validates the purification by presenting comparative results on gas composition, removal efficiencies, and calorific value tests, demonstrating the performance of the system at the Kimbiji test site.

#### Methodology

The first validation step involved assessing the quality of the raw biogas produced by the digester. Due to the absence of a sampling line in the setup, gas samples could only be withdrawn manually after the purification phase was complete. To establish a baseline

reference, a sample was drawn directly from the digester outlet and its composition was measured using the IRCD4 biogas analyzer described in Section 4.3.1.

Before the test, the entire purification system, including all connection tubes and the absorption column, was purged of ambient air by continuously pumping fresh biogas through the system while monitoring the outlet composition with the gas analyzer. Once the oxygen concentration at the outlet had dropped to 0 vol%, the system was considered air-free, and testing commenced. As a final preparatory step, the LPG tank was attached to the output, and 700 g of  $Ca(OH)_2$  was added to the absorption column.

The procedure followed was identical to that used at the university setup. When the system was activated, the LPG tank began to fill. Filling continued until the output pressure reached 8 bar. At that point, the compressor was stopped and the LPG tank disconnected.

After the test was completed, the final biogas composition was measured using biogas from the LPG tank. Although using this setup, the gas composition cannot be measured during the pressure build-up phase, the LPG tank provided a reliable overall average.

In a second validation test, the calorific value of the purified biogas was determined following the procedure outlined in Section 4.3.3. The LPG cylinder was connected to a standard LPG stove with the reducer described in 5.2.1. Because the burner lacked or had a broken integrated ignition mechanism, ignition was provided by an external lighter. This test maintained the same water bath calorimeter arrangement and burner geometry as in the experiment at the university to ensure consistency and comparability of results.

## Results and discussion

Table 5.1 illustrates the results obtained from the biogas analyzer, providing a clear comparison between the initial and final gas compositions at the Kimbiji site after treatment.

Table 5.1: Initial and final biogas composition

|        | Initial composition [vol%] | Final composition [vol%] |
|--------|----------------------------|--------------------------|
| $CH_4$ | 65                         | 82                       |
| $CO_2$ | 33                         | 16                       |
| $O_2$  | 0.5                        | 0.6                      |
| $H_2S$ | 277 ppm                    | 2 ppm                    |

The test results indicate that the untreated biogas composition is similar to the composition measured at the university, except for the  $H_2S$  content. The biogas from Kimbiji contained 277 ppm of  $H_2S$ , which is almost half the concentration found in the university sample. This final concentration of 2 ppm is well below the target threshold of 5 ppm, demonstrating effective desulfurization.

Furthermore,  $CO_2$  concentration was reduced from 33 vol% to 16 vol%, reflecting the reduction achieved in university trials. This significant decrease in the carbon dioxide content directly contributed to an increase in the concentration of methane, which increased to more than 80 vol%, thus exceeding the target value of 75%.

The  $CO_2$  removal efficiency was calculated using Equation 4.2 from Subsection 4.3.3. The result indicate that the absorption column removed 61% of the  $CO_2$ . This result is similar to the result at the university setup.

The results of the calorific value test are presented in Table 5.2. For comparison purposes, the corresponding values obtained at the university are included in the table. The heating time was measured between 40 °C and 90 °C for all samples, except LPG and untreated biogas, which were measured between 40 °C and 80 °C. Power output P was calculated using Equation 4.3, which is based on the heat absorbed by the water bath.

Table 5.2: Calorific value test results

|                             | Time [s] | P [W] |
|-----------------------------|----------|-------|
| University untreated biogas | 985      | 79    |
| University water scrubbing  | 325      | 322   |
| University absorption       | 390      | 268   |
| LPG                         | 363      | 230   |
| Kimbiji absorption          | 345      | 303   |

The results indicate that the Kimbiji absorption setup achieved a higher power output relative to the university’s absorption system. This improved performance can be attributed to the absence of air in the gas mixture, which results in a higher methane concentration and therefore a more efficient combustion process.

## Conclusion

This test demonstrated that the purification setup not only met but exceeded project requirements, proving that effective biogas purification can be achieved with locally sourced materials and simple construction methods, while still delivering a significant improvement in gas quality.

The calorific value test shows that the purified biogas outperformed the absorption setup at the university setup and LPG under identical burner conditions, validating biogas as a sustainable alternative for everyday cooking applications in off-grid or low-income settings.

### 5.3.2 Energy supply

This subsection discusses the validation of the energy supply. It focuses on voltage drop, the maximum power coming from the solar panels and the overall usability of the system.

#### Method

The solar panels were mounted and left in the sun for 2 days before testing started. According to the manufacturer, they need up to 2 days to reach ideal working conditions.

The test for the energy were conducted using 2 measuring devices. The first one is a multimeter, as outlined in Section 4.3.4. The other measuring device is the PWM controller. This unit measures battery and solar voltage, as well as the currents between the connected components.

## Results and discussion

During operations, the load on the system was slightly higher than 100 W. This is equal to the tests conducted at the university setup. This power could be fully pulled from the solar panels, even under slightly cloudy conditions and during moderate sunlight hours.

The solar panels showed good power throughput; at their maximum, they yielded over 20 A. At 4 m, the cable connecting the solar panels to the PWM controller is long. The cable has a 4 mm<sup>2</sup> diameter, is a copper cable and at 4 m the voltage drop is around 1.2 V, resulting in about 39 W lost, nearly 10% of total output. This is assuming the maximum 400 Wp. This is quite significant and at larger scale will result in even higher losses.

The inrush current proved to be high, too high for the battery and solar panels to handle. When the system is turned on, due to the high inrush currents, the battery voltage drops significantly, falling below the safety limits of the PWM controller. This drop triggered undervoltage protection, interrupting startup attempts.

Because solar batteries tend to be less sensitive to low battery voltages, this safety margin was lowered to 10 V. At this point, the compressor was sometimes able to start. If it failed to start, it was the inverter that was unable to maintain a steady output voltage. This inverter is not good at handling strong inductive loads, and that's why it failed. Its internal regulation reacts too slowly, causing voltage collapse during the initial surge required by the compressor motor. If the compressor did start, the inverter proved more reliable and the system could run stably under continuous load conditions, as the steady-state demand was within the inverter's capabilities.

## Conclusion

This test demonstrated that the energy supply met the project's requirements for a sustainable, independent power source. Once the system was running, it operated effectively and efficiently. However, starting the system proved more challenging, as the startup power demand was both too high and for the batteries to handle reliably.

## 5.4 Operational problems and maintenance

This section outlines the key operational issues encountered in the biogas upgrading system and the routine maintenance tasks required to ensure reliable performance. It discusses problems concerning the compressor, the H<sub>2</sub>S removal unit, the absorption column, and the input and output of the system.

To maintain the system, three steps are defined. These steps include replacement of the H<sub>2</sub>S and CO<sub>2</sub> absorbent materials, refilling of water in the absorption column, and water removal from the moisture traps.

### 5.4.1 Compressor

The compressor has a significant shortcoming at startup. When switched on, it draws a high inrush current. Combined with a low power factor, this often requires several attempts before the unit actually runs. There are two related issues:

The high inrush current causes the battery voltage to sag, causing the PWM controller to enter its safe mode and shut down. One way to mitigate this is to use battery technology designed to handle higher inrush currents, for example, a lead acid battery such as those used in cars. Although this will reduce the voltage drop, these lead-acid cells suffer from a relatively low cycle life [135], [136].

The high inrush current, calculated in 4.3.4, at startup leads to a significant drop in battery voltage, which in turn causes the inverter to let its output voltage collapse to 0 V. Adding a series 'start' resistor in line with the compressor motor improves the power factor and limits the initial current draw. Once the compressor is up to speed, the resistor must be bypassed (for example, by a relay) so that it does not consume power during normal operation.

Another operational issue is thermal protection: after running for more than 30 min, the compressor's internal temperature rises to a critical point, triggering its thermal cutoff. The unit must then remain off until it cools before it can be restarted.

Furthermore, since the compressor uses a membrane principle, it might be especially vulnerable to long-term  $H_2S$  degradation under these conditions. Ensuring effective  $H_2S$  removal is thus crucial.

Finally, if the discharge line remains at high pressure when the system is turned on, the unit will not engage until that back pressure has fallen to a safe level. Ensuring adequate pressure relief or bleed-off prior to each restart will prevent this lockout.

### 5.4.2 $H_2S$ removal unit

Figure 5.14 shows severe sulfur corrosion in a brass fitting installed immediately upstream of the  $H_2S$  removal unit. Because this unit is located relatively late in the preprocessing train, the untreated biogas passes through the entire preprocessing unit, exposing these parts to high  $H_2S$  levels. Over time, dissolved  $H_2S$  attacks the copper-zinc alloy (brass) of the fitting, leading to surface darkening, pitting, and eventual loss of mechanical integrity. Figure 5.14 illustrates the damage after 2 weeks of testing the university setup.

In aqueous or wet gas streams containing  $H_2S$ , brass alloys undergo a sulfidation reaction in which sulfide ions react with zinc to form zinc sulfide ( $ZnS$ ) on the metal surface. The general reaction is represented in Equation 5.1. In this reaction  $H_2$  is also formed. Since this is just a trace amount in comparison to the full gas volume, this does not influence the gas' behavior. Secondly, a slower reaction also takes place. In this reaction, as shown in Equation 5.2, copper reacts with the  $H_2S$ , forming patina. This reaction gives a greenish hue to the material [137].



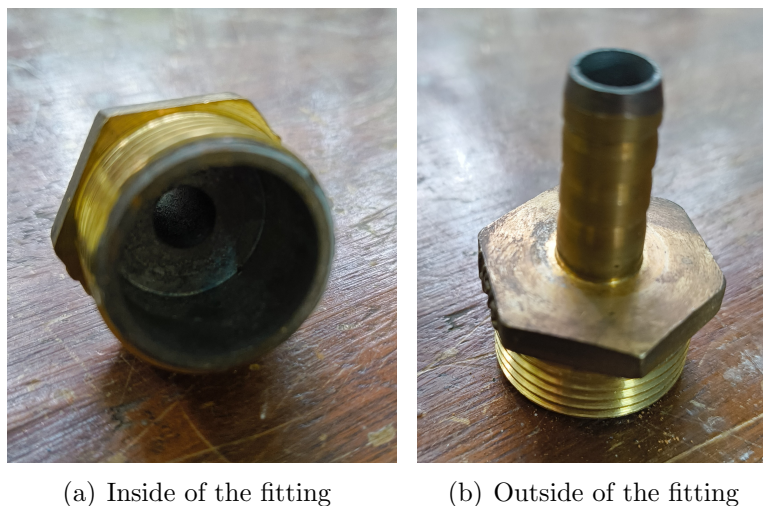
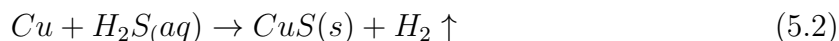


Figure 5.14: Corroded brass fitting



Once a thin  $\text{ZnS}$  layer forms, it no longer passivates the underlying metal effectively. Localized breakdown of this layer leads to pits and crevices where sulfide concentration remains high, further accelerating corrosion. Due to the air leak at the university setup,  $\text{O}_2$  was present in the gas stream, accelerating this process even more [138]. In brass, dezincification often accompanies sulfidation, weakening the microstructure of the alloy and reducing ductility. In this application, the fitting's interior, as shown in Figure 5.14(a), exhibits a matte black sulfide layer.

To prevent this corrosion from occurring, the brass fittings can be exchanged with a corrosion resistant material. For this purpose, a plastic fitting can be used, as the material does not require high strength. Several steel-based alloys can also be used as outlined in [139]. For this purpose, duplex steel or martensite stainless steel would work as alternatives [137]. If brass is a required material, at least 85 w% copper should prevent selective corrosion of the material. However, locally, only one type of fitting was available, meaning that it will have to be replaced upon failure.

The second issue with the current  $\text{H}_2\text{S}$  removal setup is the uncertainty surrounding the final biogas'  $\text{H}_2\text{S}$  content. While there is a guideline indicating when to replace the removal material to ensure adequate  $\text{H}_2\text{S}$  reduction, this guideline does not account for fluctuations in the input gas composition. Furthermore, it overlooks potential degradation in the absorbent's quality or efficiency over time. As a result, monitoring of both the input and output gas compositions is essential to ensure effective  $\text{H}_2\text{S}$  removal.

One potential solution is to integrate a permanent  $\text{H}_2\text{S}$  sensor into the system to provide real-time measurements of  $\text{H}_2\text{S}$  levels, which could allow the system to be switched off automatically. Alternatively, a different removal material could be employed, such as iron



oxide, which changes color when saturated with  $H_2S$ , offering a visual indication of when replacement is necessary.

### 5.4.3 Absorption column

The absorption column has two essential maintenance procedures. One is to verify and adjust the internal water level to maintain optimal gas–liquid contact. The second is to periodically replenish the absorbent ( $Ca(OH)_2$ ) to ensure a consistently high  $CO_2$  removal efficiency.

The first maintenance step involves replacing the absorption medium. As the column operates,  $Ca(OH)_2$  reacts with  $CO_2$  in the biogas to form  $CaCO_3$ , gradually consuming  $Ca(OH)_2$ . Periodically, the spent  $CaCO_3$  must be removed and fresh  $Ca(OH)_2$  loaded into the tank. The manual recommends replacing the material weekly with 700 g new  $Ca(OH)_2$ . The recovered  $CaCO_3$  can then be repurposed locally to stabilize the pH of soil, thereby converting a waste stream into a useful byproduct.

The challenge of this maintenance procedure lies in the inability to determine the exhaustion point of the  $Ca(OH)_2$  medium without measuring the gas outlet composition. Under a constant inlet  $CO_2$  concentration, a fixed weekly replacement interval may provide satisfactory performance. However, any increase in biogas production and therefore  $CO_2$  loading can lead to premature saturation of the absorbent, resulting in decreased removal efficiency. To address this, the replacement frequency must be adjusted to reflect actual  $CO_2$  loads or regular monitoring of the gas composition must be implemented to ensure that the absorber maintains its designed efficacy.

The second maintenance procedure involves replenishing the water inventory in the absorption column. This task is more complex, as the operator must first depressurize the column, then remove the upper coupling, add water until the indicated fill level is reached, and, finally, re-secure the connection. An underfilled column will suffer from inadequate gas–liquid contact and thus reduced absorption efficiency, while overfilling may result in water carry-over to the post processing units.

Since not all of the  $CO_2$  is removed from the biogas, less absorbent is needed. To filter out this 20 vol%  $CO_2$ , theoretically 425 g of  $Ca(OH)_2$  is required each week. After accounting for some uncertainty and system inefficiencies, instead of adding 700 g weekly, 500 g would suffice. This takes a high safety margin into account, ensuring reliable absorption even in fluctuating operating conditions or minor measurement errors in gas composition.

### 5.4.4 In- and output

When the biogas digester is connected to the system, its internal pressure is often below the minimum sensing threshold of the input pressure gauge. Because the gauge reads 0 until this threshold is reached, operators have no feedback on the actual digester pressure. This is a problem as the gauge does not give any information, and problems may be harder to detect.

After the system has filled an LPG storage tank, that tank must be unbolted and removed before the gas can be used. In the current design. The valve on the LPG tank is connected

to the system, and can only be removed from the tank by rotating the entire cylinder around it. This maneuver is cumbersome, can stress the valve, and can be dangerous if a large and heavy tank is connected. The solution could be to replace the final segment of rigid tubing with a dedicated propane hose that has a threaded connection at the end, illustrated in Figure 5.15. This unit can be easily screwed onto the LPG valve, allow the LPG valve and tank to be dismounted easily.



Figure 5.15: Propane hose connector [140]

Using this part requires the operator to rotate only the coupling nut of the hose, not the entire tank, to disengage the line. This is significantly more ergonomic and will be a good improvement over the current setup.

Finally, both the inlet and outlet moisture traps must be drained regularly to prevent water from entering the compressor or the LPG tank. Fortunately, this maintenance task is straightforward, as operators can visually verify the accumulation of water while the system remains pressurized. The manual recommends biweekly checks on these traps.

## 5.5 Proposed large-scale setup

This section presents the initial full-scale design that was originally proposed before the Kimbiji site underwent significant downsizing. While this version was not implemented, it serves as a reference for potential future expansions and offers insights into the full-scale approach to biogas upgrading, compression, and distribution.

Building on the literature review, the original design aimed to develop a scalable and efficient biogas processing system tailored to the energy needs of rural communities, particularly those in Kimbiji. The system is designed to process approximately 6,500 L of biogas per day in a fixed-dome digester, shown in Figure 5.16(b).

Initially, the site was constructed with the capacity to handle all of the Kimbiji ward's organic waste. An estimated 370 inhabitants generate approximately 300 kg of organic municipal waste, as reported in [141]. Figure 5.16(b) shows the status of the digester, which features a projected capacity of 25,000 L. While the foundation is complete, budget constraints have halted further progress. Currently, a smaller 3,000 L floating-drum is temporarily inside the incomplete fixed-dome.

The full-scale purification and compression setup incorporated insights from the prior implementations while addressing practical constraints such as resource availability, cost-



Figure 5.16: The current Kimbiji large-scale setup

effectiveness, scalability, and environmental sustainability. The selection of components, considerations for energy supply, and structural configurations were specifically adapted to the conditions in Kimbiji, prioritizing reliability and functionality.

### 5.5.1 Proposed concept

The proposed full-scale design is depicted in the flowchart shown in Figure 5.17. This system employs a water scrubbing process, which is more suitable at this scale compared to the absorption method. The absorption setup would require approximately 6.5 kg of  $Ca(OH)_2$  per day to meet the biogas purification demands. In addition to the high material replacement cost, the frequent handling and replacement of  $Ca(OH)_2$  would require considerable time and labor. In contrast, the water scrubbing system operates with minimal maintenance and does not require such frequent material replacement, making it a more practical and sustainable choice for large-scale implementation.

This system will be designed to handle an input of 6,500 L of unfiltered biogas per day. From the data at the university setup, it would be able to fill 58 small biogas tanks per day at 8 bar pressure, providing approximately one meal per day for as many families. An additional input is required in this system. For this design, air will be forced into the desorption column. In this design, ambient air is forced into the desorption column. This untreated air absorbs the  $CO_2$  from the water and is then vented back into the atmosphere.

The setup remains broadly similar to the initial water scrubbing configuration described in 3.1.1. The preprocessing unit is identical in concept to the original design. Changes have been made to the water scrubbing, post processing, and energy supply setup.

The greatest change focuses on the water scrubbing unit, where removal efficiency is increased in two ways. First, a pressure relief valve installed immediately downstream of the scrubber allows the column itself to operate at elevated pressure, optimizing  $CO_2$  absorption, by keeping the scrubbing pressure constant. This ensures stable and consistent removal efficiency.

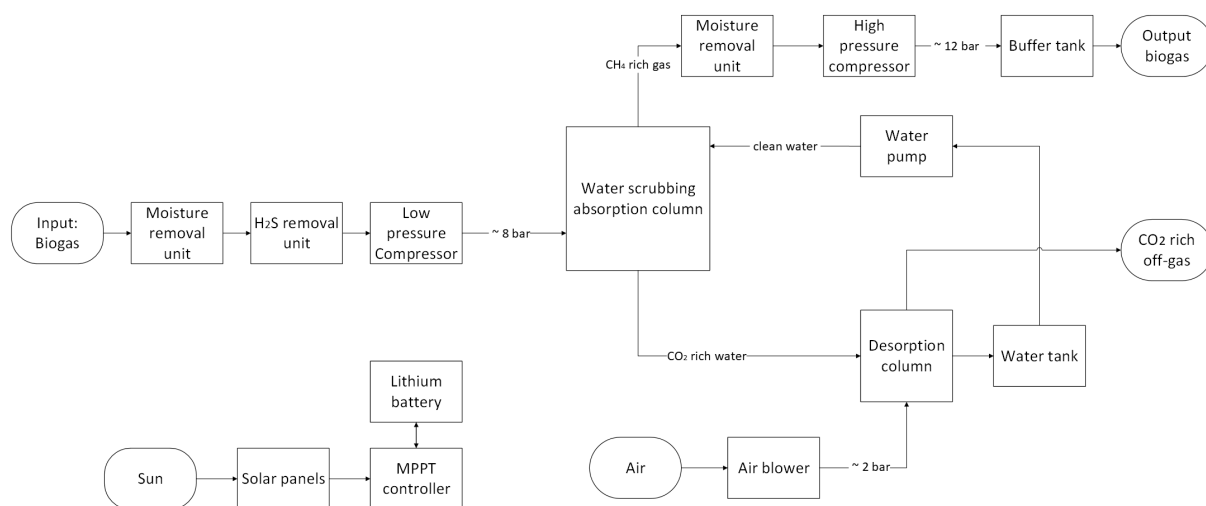


Figure 5.17: Process flowchart for the Kimbiji setup

The second enhancement targets the water scrubbing column itself. By introducing turbulence-inducing internals, such as structured packing or random packing spheres, the gas–liquid contact area and residence time are substantially increased. This boosts mass transfer and enables greater  $CO_2$  removal.

The desorption column is housed in a dedicated tank separate from the main water reservoir, enabling daily removal of up to 1,950 L of  $CO_2$  from the scrubber liquid. By maintaining a low  $CO_2$  partial pressure above the liquid, achieved by continuously blowing air through the desorption column, the dissolved gas is efficiently stripped and vented. This ensures the circulating water remains lean in  $CO_2$  and the scrubbing cycle performs well. This air is introduced into the desorption column by an air blower. This blower does not have to be as powerful as the compressor, as the desorption column operates at atmospheric pressure.

An additional compressor could be included in the post processing stage to increase the gas pressure. Higher pressures allow more gas to be stored in the same tank volume, thereby extending cooking duration. Higher pressures would improve the usability of the biogas, as the cooking time improves with the same volume of LPG tank. Standard LPG tanks are rated for pressures over 20 bar, they would remain suitable for use under elevated pressures.

Elevated operating pressures introduce two significant drawbacks. Firstly, to prevent leaks under these conditions, sections of the piping must be constructed from brass to achieve a gastight seal. This complicates installation, as brazed connections are required, and also increases material costs. Secondly, the standard pressure reducers used in LPG, the same ones used in these biogas systems (see Figure 5.9), are rated for overpressures of up to 7.5 bar. Exceeding this limit renders them ineffective and necessitates the use of different reducers. Section 2.4.3 of the literature review notes that 10% of biogas systems fail due to a lack of compatible appliances. Requiring users to install a specialized high-pressure reducer, instead of a standard LPG regulator, would substantially increase the likelihood of system failure. Consequently, no additional compressor will be incorporated into this design.

In this configuration, multiple output lines are added. This enables continuous operation of the system during tank exchanges. Additionally, filling several tanks simultaneously can extend the interval between operator interventions, improving the autonomy of the system.

The system is powered by solar panels and a combination of a solar battery and a car battery, which are connected to an MPPT controller. The MPPT controller optimizes battery charging by regulating voltage to increase the efficiency of the solar panels. The battery pack is designed to support operation on moderately cloudy days, though the system will not function during dark days nor at night, this would make the battery pack too expensive. The car battery will handle the inrush currents drawn by the motors, while the solar battery improves the longevity of the system. By combining both technologies, a cost-effective yet efficient battery pack can be built.

This proposed design offers a sustainable, efficient, and low-maintenance biogas purification system suitable for large-scale use, balancing performance, usability, and cost while ensuring consistent gas quality.

## 5.5.2 Component selection

This subsection discusses the proposed selected components and implementation of the Kimbiji setup. It focuses on the difference between the current Kimbiji setup and the large-scale setup.

### Preprocessing

The current system is capable of producing 112 L of biogas in 10.6 minutes, or approximately 634 L/h if continuous operation is possible. To process the daily Kimbiji production, the current system would run 10 hours and 12 minutes. Compared to the 11 hours of sunlight (see Section 2.3) , this system would, in theory, just suffice.

However, the current system cannot run continuously, as cloud cover reduces sunlight hours, and the existing refrigerant compressor is not designed to run for extended periods. To address this, a larger compressor has been selected. The chosen model, the ADW77 refrigerator compressor [130], has a displacement of  $7.7 \text{ cm}^3$ . This unit has 1.79 times the displacement of the current compressor and is capable of processing the daily Kimbiji production in approximately 5 hours and 42 minutes. This allows for alternating on-off cycles, providing enough time for the compressor to cool down or for the batteries to recharge as needed, while still completing the full daily processing.

The ADW77 is slightly more expensive at TZS 177,000 compared to the current model's TZS 141,000. It also consumes more power at 185 W compared to 110 W. Despite these drawbacks, it offers a significant improvement in processing capacity and operational flexibility.

Aside from the compressor, the rest of the preprocessing setup remains largely unchanged from the university configuration. The only concern with reusing the current setup is that it was originally designed and tested for operation under the low gas pressures typically produced by a floating-drum digester. If the fixed-dome digester generates gas at higher pressures, there is a risk that this part of the system experiences leakages or mechanical

failure. This issue requires careful validation during the implementation of the large-scale system.

The  $H_2S$  removal material selected for this setup is granulated  $Fe_2O_3$ . While rusted steel wool, as used in the current Kimbiji setup, has proven effective, sourcing sufficient quantities of it in a rural setting may be difficult and costly. For this reason, granulated  $Fe_2O_3$  was chosen as a more practical and scalable alternative. In addition to its high removal efficiency and low cost, another key advantage of using  $Fe_2O_3$  is its change in color, changing as it absorbs  $H_2S$ . This provides a clear and reliable cue for when the material needs to be replaced, even if  $H_2S$  concentrations fluctuate.

The raw biogas in the current Kimbiji setup contains 277 ppm of  $H_2S$ . Assuming that this concentration remains constant, approximately 4.6 g of  $Fe_2O_3$  would be needed per day to effectively remove the  $H_2S$  present, at an estimated daily cost of TZS 21.47 (as outlined in Section 3.2.2). A higher  $H_2S$  concentration would substantially raise this cost. In the worst case, the biogas could contain 20,000 ppm  $H_2S$ , this cost would increase to TZS 2,214 per day.

### **Water scrubbing setup**

The structured packing intended for this setup was unavailable at Kariakoo. However, it is possible to procure it online or fabricate it locally using materials such as PVC bottles. These elements serve to induce turbulence in the flow, so any irregular shape would be effective in this role. Constructing the packing from PVC waste aligns with Kimbiji's broader goal of transforming waste into usable resources. However this packing material has to be tested before using to evaluate its performance.

The pressure washer used in the university setup proved unable to reach pressures over 5 bar. At 5 bar, the removal efficiency was inadequate, and the 8 bar is required for effective gas storage. An alternative solution is to use booster pumps typically found in household water filtration systems. Section 3.3.2 outlines the required water flow as 3.3 L, adjusted for the 1.8 timer higher gas flow rate. A model available at the Kariakoo market is identified in [142]. While each unit delivers only 2.6 L/min, which is insufficient on its own. However, installing two pumps in parallel meets the required flow rate. Each pump consumes 77 W of power, offering a more energy-efficient alternative to the pressure washer.

The desorption column in this design is constructed with the same components as the water scrubbing column. To force air through the desorption column an air blower is used. As an initial proposal, a biogas booster pump is used, as this was available in a local store. These blowers are capable of blowing large quantities of air, while still having sufficient pressure build up. The proposed blower costs TZS 100,000 and has a rated power of 20 W.

### **Energy supply**

The energy system must supply sufficient power for both the compressor and two pumps. The estimated total power requirement is approximately 360 W. In this proposal. No additional margin is allocated for lighting at the site as this required quantity is unpredictable. This should be recalculated once lighting requirements are known.

The pump runs directly on 24 V DC, so it can be connected straight into the controller without an inverter, eliminating an extra conversion stage, minimizing energy losses, and boosting overall efficiency. However, wiring a 24 V load directly into the DC bus introduces safety concerns. Without proper short-circuit and over current protection, a fault could draw extremely high currents, leading to cable overheating, connector damage, or even fire. To safeguard the system, the pumps are connected to the AC-side, as losses are not huge and this improves safety. A DC power source was selected. A small 3 A DC-supply was selected for each water pump. Once the unit is connected, it has to be validated to ensure it can supply sufficient .

Aside from the inverter, the existing PWM controller is fully adequate for this application. In its current configuration, the solar array is rated 400 Wp. To meet the demands of the large-scale setup, changing these panels to two 500 Wp panels will provide the necessary extra capacity to deliver the 360 W consistently [86].

The battery pack consists of two 12 V, 50 Ah units: a deep-cycle solar battery and a starter-type car battery. The solar battery is a sealed lead-acid type, whereas the car battery is a flooded lead-acid type. The solar battery offers a long service life but is vulnerable to the high inrush currents generated by the compressor, whereas the car battery tolerates these surges more effectively at the expense of a shorter lifespan. By pairing them in parallel, the system achieves a compromise, retaining durability while handling transient loads. Each battery has a cost of approximately TZS 175,000 each.

### 5.5.3 Implementation and component pricing

This subsection discusses the proposed implementation for the larger Kimbiji site. It discusses how the components can be installed. At the end of this subsection, an estimate for the full cost of the components is made. However, this is just a rough estimate as the implementation is not yet done.

The implementation of the large-scale setup is similar to the one installed at the Kimbiji site. However, this setup can be mounted directly onto a wall, eliminating the need for a wooden panel as used in the current configuration. As a result, there is no risk of water damage to the wooden panel, since it is no longer required.

#### Purification and compression implementation

The design assumes that the biogas hose can be connected directly to the digester without requiring additional fittings. It is important to monitor the pressure inside the digester to ensure that it remains within operating range for the preprocessing components to not break due to excessive pressure. Excessively high pressure could damage components within the system or lead to operational failures.

The preprocessing setup is identical to the one described for the Kimbiji setup in Section 5.2.1. The only component that differs is the compressor. This compressor can be connected to the system in the same manner as the previous one.

The subsequent modification pertains to the material with absorbing properties. The  $H_2S$  filter must be filled with granulated  $Fe_2O_3$ , which requires regular replacement. Timely replacement of the absorbent is crucial, lack of doing so would result in damaged

components. The color of the material serves as an indicator: once it turns completely black, it must be replaced with fresh granulated  $Fe_2O_3$ .

The current Kimbiji setup can be upgraded to a water scrubbing system with minimal modifications. By drilling an additional hole into each endcap and securing a PVC threaded female socket with PVC glue. The lower socket connects to a desorption tank, from which a pump circulates water back to the top socket of the scrubbing column. The second upper socket connects to the water pumps. If, however, the setup would be build from scratch, this same configuration can be made.

The water scrubbing system itself closely resembles the configuration used at the university, with two major differences. The water scrubbing column is approximately 1.5 m and the new structured packing is placed inside the water scrubbing column.

The second key difference is the water pump. In this setup, two pumps operate in parallel. When implementing this design, special attention must be given to the connections between the hoses and the high-pressure side of the compressor, as these connections were not verified during the project and may require reinforcement or redesign.

The third difference concerns the desorption column. In the university setup, water flowed directly out of the scrubbing column without further treatment. However, in the large-scale setup, more than 1,300 L of  $CO_2$  is expected to be extracted daily. Under such conditions, the basic university setup may be insufficient, as  $CO_2$  could accumulate around the tank, reducing removal efficiency.

To mitigate this, the proposed design includes a separate desorption column in which water is sprayed down a 50 cm vertical PVC tube while air is forced in from below. This column features one PVC threaded female socket connection at the top, and two at the bottom. This active ventilation helps maintain a low  $CO_2$  partial pressure above the water, improving desorption efficiency. It is important to ensure that the blower is positioned above the water tank to prevent water damage.

The post processing assembly differs only at the output. Here, brass T-fittings allow up to five tanks to be filled simultaneously. This reduces operator workload and allows the system to work continuously.

The complete proposed implementation is provided in Attachment F.1. This schematic gives a basic overview of the required components and how they should be connected. To accompany this schematic, a detailed list of all necessary components, along with their prices, is presented in Attachment G.1. Although not all of these parts were acquired during the project, their availability and price were verified in the Kariakoo market.

## **Energy supply**

The implementation of the energy supply differs from the current setup in Kimbiji. In the existing configuration, all components are mounted together on a wooden board. This setup also includes a long cable between the solar panels and the charge controller, which result in significant efficiency losses in the DC wiring.

For the larger-scale setup, two separate electrical boxes are proposed to improve performance. The first box should be mounted under the roof, in close proximity to the solar



panels, to reduce the DC cable length. This enclosure houses the MPPT controller, batteries, and inverter. The batteries should be connected in parallel. As these lead-acid batteries have a limited service life, periodic replacement is necessary.

From the inverter, an AC cable runs to the second electrical box, installed near the purification and compression setup. This box must be easily accessible, as it contains the system controls. Within this enclosure, the AC power is distributed to the compressor, blower, and two water pumps. A DC power supply is installed to supply the pumps with 24 V DC.

Each energy-consuming component is connected through a circuit breaker for protection and individual control.

Attachment F.2 outlines the entire proposed implementation in detail. This schematic provides an overview of the components required and their interconnections within each electrical box. To support this diagram, a detailed component and pricing list is provided in Attachment G.2. Although not all listed items were purchased, their availability and pricing were confirmed in the Kariakoo market, ensuring accuracy and feasibility.

### **Component pricing**

Component costs of the current system are presented. The prices are all tax included. In Tanzania, a standard 18% VAT tax applies to these purchases. The total cost can be divided into three categories: investment costs, maintenance costs, and inventory holding costs. A complete bill of materials is provided in Attachment G.

The investment cost for the purification and compression is estimated at TZS 1,057,980 (EUR 348.62). This includes components such as the blower and the desorption column. The energy supply requires a higher initial investment of TZS 1,890,750 (EUR 623.03). While this cost is relatively high, it covers a sustainable, off-grid power solution, reducing long-term dependency on external power sources. This brings the full capital cost of the purification and compression setup to TZS 2,948,730 (Eur 971.65).

To keep the system running efficiently, two components require regular replacement. The first is the  $H_2S$  absorbent material, which is expected to cost approximately TZS 21.5 per day (or less than EUR 0.01 per day). The second is the battery pack.

# Chapter 6

## Techno-economic analysis

In a world where energy is both a catalyst for development and a reflection of inequality, the true value of an energy system lies not only in its technical performance, but in its ability to be economically viable [128], [7]. This chapter aims to determine whether the proposed biogas purification and compression systems, powered by solar energy, can meet this challenge.

To this end, a comprehensive TEA is conducted, integrating both financial evaluation and comparative benchmarking. Section 6.1 begins with the methodological framework, outlining the analytical tools and assumptions that shape the remainder of the chapter. A discounted cash flow (DCF) approach forms the foundation of this evaluation, allowing for time-value-adjusted cost estimation and investment analysis.

In the following section, the total cost of both the current small-scale and proposed large-scale systems is systematically broken down into capital expenditures, operational expenses, and inventory holding costs, culminating in a consolidated overview of the complete cost profile. This is followed by a financial evaluation including a net present value (NPV) analysis and the discounted payback time (DPT), offering insight into both the long-term return and the time required to recover the initial investment considering time value of money. Subsections include the structure of the NPV model, break-even analysis, and biogas pricing scenarios.

The next section then transitions into a comparative analysis with realistic alternatives. These include conventional fuel sources, fully solar-powered systems, and a hybrid solar-biogas configuration. Each alternative is evaluated not only on capital intensity and energy output, but also through a levelized cost of energy (LCOE) comparison to ensure fair assessment on a per-kWh and per-meal basis.

The chapter concludes with a discussion. Key topics include the identification of dominant cost drivers, a sensitivity analysis across selected parameters, considerations around scalability for wider deployment, and a reflection on political influences that may shape the implementation potential of these systems in practice.

## 6.1 Methodology

This section outlines the methodology used for the TEA. It details the analytical framework, including the economic perspective, comparison basis, and scenario design. All underlying assumptions regarding labor, digester pricing, discount rate, lifespan, maintenance and time horizon are also discussed.

### 6.1.1 Analytical framework

The analytical framework defines the scope and approach of the TEA, establishing the rationale behind the adopted evaluation criteria.

#### Economic perspective

The analysis is conducted from the viewpoint of a rural community aiming to reduce dependence on traditional biomass and fossil fuels. All costs are based on local prices and reflect real-world implementation conditions. Capital expenditure (CAPEX), operational expenditure (OPEX) and maintenance costs are included. The objective is to identify the most cost-effective and sustainable energy solution under practical constraints.

#### Scenario comparison

The primary focus of this thesis is a small-scale system designed to purify and store 100 L of biogas per day. In addition, a large-scale design capable of processing 6,500 L/day, 65 times more, was introduced in Section 5.5. These two system sizes are compared in terms of economic performance.

For each case, biogas is benchmarked against commonly used regional fuels: firewood, charcoal, grid electricity and LPG. Furthermore, an alternative use of solar energy is considered. Instead of powering the compressor, solar energy could directly serve cooking purposes. Hybrid systems combining solar-powered biogas upgrading and cooking are also evaluated.

#### Comparison basis

Economic performance is evaluated using NPV and DPT. From these, a break even cost per kWh is derived and compared to the market prices of alternative fuels.

All energy-related costs are normalized per kWh of useful energy. This normalized metric is referred to as the levelized cost of energy (LCOE). To provide a fair end-use comparison, combustion efficiencies of each fuel are also considered. Since these efficiencies were not experimentally determined, they are estimated from literature data.

### 6.1.2 Assumptions

This subsection outlines the key assumptions used in the TEA. These assumptions are selected to reflect the realities of a rural Tanzanian context while maintaining analytical transparency and reproducibility. The values and simplifications made here are important to interpreting the outcomes of the TEA.

## **Labor and working hours**

Labor costs are not included in this analysis. While contracting an external firm for system construction would significantly increase capital expenditure, such an approach is not representative of the local implementation model. In most rural communities, construction and installation are typically carried out by local actors, often on a voluntary or low-cost basis. Therefore, labor is not treated as a financial cost within this study.

## **Digester pricing**

The biogas digester itself was not designed within this thesis, but by a previous project conducted at the same site. That project also provided capital cost estimates. However, their cost allocation included broader project overheads and logistical margins, resulting in inflated figures not directly applicable to a community-level implementation. For consistency, the digester's cost is recalculated based on direct material and fabrication costs, using the same pricing method applied to the rest of the system. This is discussed in Section 6.2.

## **Discount rate**

A discount rate of 5% is applied to account for the time value of money, reflecting that future costs and revenues are worth less than their present, day equivalents. While the biogas produced could, in principle, appreciate in value due to inflation, discounting remains appropriate to reflect investment opportunity costs and economic risk. The 5% rate aligns with literature on rural energy projects in Sub-Saharan Africa and is considered a conservative estimate, given the limited access to capital and elevated investment risk in such contexts [143].

## **System lifespan**

A system lifespan of 10 years is assumed. Literature suggests longer operational lifetimes, typically 15–20 years for biogas systems [144]. However, this study adopts a more conservative value due to harsher environmental conditions, limited technical expertise and minimal preventive maintenance practices in rural Tanzanian settings. Shorter-lived components are taken into account through periodic replacement in the maintenance cost model.

## **Maintenance**

Maintenance costs include part replacement, biogas leakage, and unplanned downtime. Although routine maintenance is performed locally, more complex failures, such as battery failure, may require assistance from outside of the community. Labor associated with maintenance is not taken into account, for the same reasons outlined above.

## **Time and cost perspective**

All costs are expressed in Tanzanian shillings (TZS), if prices are given in euro, an exchange rate of 3,034.78 TZS/EUR was used (exchange rate on 08/06/2025). All components were purchased between February and May 2025. All prices in this analysis are VAT included. Where relevant, inflation adjustments are made to express costs in 2025 price levels. It is important to note that the acquisition of components was handled by foreigners. As such, certain prices may be inflated relative to what would be possible

through local procurement in informal markets. Perceived wealth and unfamiliarity with local negotiation norms may have led to costs which were higher than typical. This is a known challenge in international development work and is taken into account in the sensitivity analysis [145].

## 6.2 Total cost

This section presents the total techno-economic cost breakdown for both the small-scale and large-scale biogas setups. Costs are first divided into CAPEX, OPEX, inventory holding costs, and then presented in a final summary table.

### 6.2.1 Capital cost

This subsection will discuss the capital costs of the small-scale and the large-scale system. The main CAPEX are the purification system, the energy supply and the digester.

#### Small-scale

The capital cost of the small-scale setup includes three main components: the biogas digester, the purification system, and the solar energy supply. An additional minor component is the grinder required for feedstock preprocessing.

The floating-drum digester used in this scenario also contributes significantly to the total capital cost. A parallel project estimated the total expenditure for its construction at TZS 2,882,000 [141]. However, this figure includes several cost components that are not representative of the final system design. For instance, it accounts for labor expenses amounting to TZS 600,000, as well as TZS 369,000 worth of components from the previous, now-abandoned filtering system. In addition, TZS 600,000 was spent on cement and brickwork, despite the fact that the digester was ultimately constructed directly on soil without the need for a masonry foundation. When these non-essential costs are excluded, the revised capital cost of the digester is estimated at TZS 1,313,000 (EUR 432.65), which more accurately reflects the system as it is currently implemented.

The preprocessing of feedstock for the digester, such as grinding or mixing, requires the aid of machines. The grinder and mixer were built by students of Ardhi University and can be used for multiple projects in the future, no cost will be incorporated for these parts in this cost analysis.

The purification system is capable of handling significantly more than the daily throughput of 100 L untreated biogas. As discussed in 4.4.2, the complete daily biogas production can be processed in approximately 10.6 min. Downsizing the unit would only marginally reduce costs while potentially compromising robustness or future scalability. The total cost of the setup is TZS 432,720 (EUR 142.59). Key cost drivers include:

- the compressor at TZS 141,000,
- the high-pressure PVC-U 2 inch piping and valve at TZS 68,800.

The energy system is intentionally oversized. It consists of 400 Wp of solar panels, a lead-acid battery, a PWM controller, a small inverter and other small parts. The CAPEX of this subsystem is TZS 953,750, with the main costs as follows:

- 2 solar panels (12 V, 400 Wp) at TZS 500,000,
- the battery (12 V, 50 Ah) at TZS 170,000,
- the PWM charge controller (12 V, 60 Ah) at TZS 130,000,
- the inverter (12 V, 220 V) at TZS 80,000.

This energy infrastructure is overdimensioned for the purification system. The compressor is the only energy consumer at 110 W and it operates less than 1% of the time. Since the same energy system can also be used for additional purposes, such as lighting or phone charging, not all of the cost is attributed to gas purification. To try and estimate the fraction of cost assigned to the biogas plant, the energy use of the compressor is compared to the total energy produced by the solar panels. Over the full span of the day, there is an average of DNI of  $4.8 \text{ kWh/m}^2$ , given the 400 Wp solar capacity, this translates to 1920 Wh energy production daily. If the compressor would run 10.6 minutes daily at 110 W, this would be 19.4 Wh [86]. These numbers show that the energy used for purification is just over 1% of the produced energy daily, attributing the cost this way would underestimate the cost. The cost can be assigned in another way, the compressor can be assumed to be running only during the peak sun hour of the day. The average peak hour had a DNI of  $553 \text{ Wh/m}^2$  [86]. With this irradiance, the solar output would be 221 W, which means that about half the solar energy installation is available for other uses. 50% of the energy supply will be assigned as CAPEX for this project. This puts the total CAPEX for the energy supply at TZS 476,875 (EUR 157.14).

Taken together, these components lead to a total small-scale CAPEX of TZS 2,222,595 (EUR 732.38).

### Large-scale

The large-scale system processes approximately 6,500 L/day, 65 times greater than the small-scale setup. This scale-up affects the upgrading system, the energy supply, and the digester.

The purification unit is now based on water scrubbing instead of absorption, its capital cost is higher, at TZS 1,057,980 (EUR 348.62). Key cost drivers include:

- the compressor at TZS 177,000,
- 2 booster pumps at TZS 380,000,
- the biogas booster pump at TZS 100,000.

Unlike the small-scale version, this unit must operate for extended durations daily. This increased runtime necessitates a significantly more robust energy system. The required solar capacity, battery storage, and inverter size are scaled accordingly. A preliminary estimate places the total energy system cost for the large-scale application at TZS 1,890,750, assuming proportional cost increases in panel area, battery capacity, and inverter power

rating. This can be refined once load profiles and local solar irradiance data are fully analyzed.

The digester for the large-scale system is a fixed-dome type. The cost of such digesters can vary widely depending on design, materials, and local availability. No reliable cost estimate is currently available. A prior study has estimated a total cost of TZS 23,232,400 (EUR 7,655.39), this value will be used as an indicator for the full cost [141].

In contrast to small-scale, the machines for grinding or mixing will need to be able to process more feedstock. Since there is no estimated cost for these, no cost will be incorporated in this cost analysis.

This amounts to a total of TZS 26,181,130 (EUR 8,627.04), with the digester being the largest contributor.

## 6.2.2 Operational cost

In both the small- and large-scale setups, the main operational costs arise from absorbents used in gas purification and from battery replacement. Labor and general maintenance costs are assumed to be negligible due to the low daily operating time and community-based operation.

### Small-scale

One recurring cost in the small-scale system is the purchase of  $Ca(OH)_2$ , used for  $CO_2$  removal. As discussed in 3.4.1, approximately 60.5 g is required per 100 L of biogas processed, which corresponds to the daily production. With a price of TZS 1,400 /kg, this results in a weekly cost of TZS 600 and an annual cost of TZS 31,311. In this cost, possible loss of absorbent is not taken into account, as this will have to be practically determined.

Iron wool and other corroded iron materials can be used to remove  $H_2S$  from the gas stream. The capacity of these materials is highly variable and depends on the available surface area. For the small-scale setup, sufficient quantities can generally be collected as waste material. As such, since operation will be done by the community, this is not considered a cost-bearing component in the operational budget.

Maintenance and unplanned downtime are, of course, critical to any long-term operation. However, in this case, the system only runs for approximately 10 minutes per day. This means any minor failure or interruption can typically be recovered the next day without impacting gas yield, as the digester acts as a buffer. Moreover, maintenance can be scheduled during idle periods. Therefore, no cost is allocated for downtime or routine maintenance. The preprocessing of feedstock for the digester, such as grinding or mixing, can be performed manually or with the aid of a simple machine. Since community members are expected to perform this task themselves, labor costs are not included.

One cost that does need to be accounted for is battery replacement. The purification system does not consume sufficient power to discharge the batteries. However, additional loads, like lights in the evening, can do this. The current system uses a lead-acid battery with an estimated DoD of 50%, allowing for approximately 1,000 charge cycles [136]. At

one cycle per day, this results in an expected lifespan of close to three years. This cost should not be taken into account for the purification. However, due to the high starting currents drawn by the compressor, which causes sulfation and heat damage, the effective lifespan of the battery is reduced [146]. Replacement is assumed every three years. The cost of the new battery is TZS 170,000, this cost is fully attributed to the setup, at an annual cost of TZS 56,667.

All these operational costs combined lead to an annual OPEX of TZS 87,978 (EUR 28.99).

### Large-scale

The large-scale configuration differs significantly in terms of gas purification. Here, water scrubbing is used for  $CO_2$  removal. Since the system relies solely on water, no direct operational cost is attributed, provided clean water is readily available. Should water need to be pumped or collected, these infrastructure costs would need to be considered, but they fall outside the scope of this study. For  $H_2S$  removal, the required quantity of rusted iron wool or similar materials scales with the gas volume. While some material may be sourced as waste, this becomes increasingly impractical at higher volumes. The excess demand needs to be met by purchasing commercial  $Fe_2O_3$  granules. For this analysis, as a simplification,  $Fe_2O_3$  is estimated to be the only absorbent, accumulating to 4.6 g of absorbent required daily. With a cost of TZS 4,667 /kg, this amounts to an annual cost of TZS 7,841.

As with the small-scale case, downtime is unlikely to affect overall performance, and no maintenance cost is accounted for. The battery is assumed to degrade at a rate similar to that in the small-scale system, as the setup allows continuous operation and is subjected to only a single daily inrush current. Battery replacement costs are estimated based on an assumed three-year lifespan, yielding an annualized cost of approximately TZS 96,667, derived from the total replacement cost of TZS 290,000. This remains an approximation in the absence of empirical field data.

All of these operational costs combined lead to an annual OPEX of TZS 104,508 (EUR 34.44).

## 6.2.3 Inventory holding cost

Some components of the system, particularly gas storage cylinders and chemical absorbents, require inventory to be held on site to ensure continuous operation. These items retain their value over the lifespan of the system.

### Small-scale

In the small-scale system, at least five LPG cylinders are required to allow buffer capacity for gas collection, storage, and flexible usage. With a unit price of TZS 20,000, the total inventory cost for storage cylinders amounts to TZS 100,000. In addition,  $Ca(OH)_2$  is used for  $CO_2$  removal and must be stocked in sufficient quantities. Given the weekly consumption of 424 g, a monthly buffer of at least 10 kg is recommended. At a price of TZS 1,400/kg, this results in a stock value of approximately TZS 14,000. Other inventory, such as small replacement parts or operating equipment, can be acquired locally at minimal cost and is estimated at TZS 10,000. Iron wool or other rusted metal used for  $H_2S$



removal is considered free, as it is assumed to be sourced as scrap material. The total small-scale inventory holding cost is therefore approximately TZS 124,000 (EUR 40.86), with LPG cylinders being the most prominent contributor.

### Large-scale

The large-scale setup does not use  $Ca(OH)_2$  and thus has no holding cost for  $CO_2$  removal. However, it requires significantly more gas storage. With an estimated daily production of 6,500 L of biogas and roughly 112 L needed to fill a single LPG cylinder, approximately 58 cylinders are needed each day. To allow for filling cycle and transport flexibility, a buffer stock of 5 days is considered minimal, resulting in 290 cylinders. At TZS 20,000 per unit, this leads to an inventory cost of TZS 5,800,000. Spare parts requirements are similar to the small-scale setup and are again estimated at TZS 10,000. The material used for  $H_2S$  removal should have a minimum stock of one month, resulting in 0.14 kg of stock. This is less than one bag. Since one bag has a price of TZS 3,500, this will be the stock. The total inventory holding cost for the large-scale system is thus estimated at TZS 5,813,500 (EUR 1,915.63), largely on account of the LPG cylinders.

### 6.2.4 Total cost

To summarize the CAPEX, OPEX, and inventory holding cost, an overview table is provided. Table 6.1 summarizes all costs.

Table 6.1: Cost breakdown for the small- and large-scale biogas system

| Cost category                 | Small-scale [TZS] | Large-scale [TZS] |
|-------------------------------|-------------------|-------------------|
| <b>CAPEX</b>                  |                   |                   |
| Purification system           | 432,720           | 1,057,980         |
| Energy supply (allocated)     | 476,875           | 1,890,750         |
| Digester                      | 1,313,000         | 23,232,400        |
| Feedstock preprocessing       | 0                 | 0                 |
| <b>Total CAPEX</b>            | 2,222,595         | 26,181,130        |
| <b>OPEX (annual)</b>          |                   |                   |
| $Ca(OH)_2$                    | 31,311            | 0                 |
| $H_2S$ absorption             | 0                 | 7,841             |
| Maintenance & downtime        | 0                 | 0                 |
| Battery replacement           | 56,667            | 96,667            |
| <b>Total annual OPEX</b>      | 87,978            | 104,508           |
| <b>Inventory holding cost</b> |                   |                   |
| LPG tanks & stock             | 124,000           | 5,813,500         |
| <b>Total (year 0 &amp; 1)</b> | 2,434,573         | 32,099,138        |

## 6.3 NPV analysis

This section presents a NPV analysis to assess the economic viability of the biogas purification and compression system under different scaling scenarios. By applying a DCF method, the profitability of the system is evaluated over a 10-year project lifetime. Two configurations are considered: a small-scale system designed for household level use, and a large-scale setup suitable for community level energy demand.

The first subsection outlines the general NPV framework and the equations. The second subsection presents a break-even analysis to determine the minimum biogas price required for financial feasibility. The final subsection examines how biogas pricing influences both NPV and DPT, providing insight into the system's sensitivity to market conditions.

### 6.3.1 NPV framework

To evaluate the profitability of the system, a DCF approach is adopted. Within this framework, each year's net cash flow is discounted back to its present value using a 5% discount rate. Summing these discounted values over the full lifespan of the system yields the NPV, which is used as the principal indicator of economic performance in this analysis.

The revenue stream is the energy content of the filtered biogas. OPEX, CAPEX, maintenance and inventory holding costs are also incorporated in the analysis. These are explained in detail in 6.2. The revenue generated through the sale of biogas is expressed in Equation 6.1.

$$R_{\text{biogas}, t} = P \cdot 365.25 \cdot D \cdot (1 - r)^t \quad (6.1)$$

In This equation,  $R_{\text{biogas}, t}$  denotes the biogas revenue in year  $t$ ,  $P$  is the biogas price in TZS/kWh,  $D$  is the average daily production in kWh, and  $r$  is the discount rate. The total revenue  $R_{\text{biogas}, \text{total}}$  over the system's lifespan  $L$  is given by Equation 6.2.

$$R_{\text{biogas}, \text{total}} = \sum_{t=1}^L (P \cdot 365.25 \cdot D \cdot (1 - r)^t) \quad (6.2)$$

#### Small-scale

In the small-scale case, the system filters approximately 100 L of biogas per day. The measured input biogas concentration in the current setup was 65%. When excluding air, 67% of the biogas would be methane. Assuming this is the average input methane concentration, this results in 67 L of methane under standard conditions. The energy content of methane is 8,560  $kcal/m^3$  at atmospheric conditions [147]. This translates to approximately 0.67 kWh per day for this setup. Over a full year, this corresponds to roughly 246 kWh of usable biogas energy.

Given this fixed production level and the assumed discount rate of 5%, Equation 6.1 can be simplified for this case, this is given in Equation 6.3.

$$R_{\text{biogas}, t, \text{small}} = P \cdot 246 \cdot (0.95)^t \quad (6.3)$$

In the DCF analysis, CAPEX, annual OPEX, and inventory holding costs are incorporated. Attachment H.1 presents the full NPV calculation, year by year. The cash flows are listed in both nominal terms and discounted terms, culminating in a final NPV value. As no fixed biogas price is assumed, the model allows for parametric analysis based on varying  $P$ . Equation 6.4 shows the formula for NPV relative to biogas price. For the

small-scale setup, the total discounted cost of ownership is calculated at TZS 2,943,094 (EUR 969.79).

$$\text{NPV} = \sum_{t=1}^{10} (P \cdot 246 \cdot (1 - 0.05)^t) - 2,943,094 \quad (6.4)$$

### Large-scale

For the large-scale setup, the system is designed to process approximately 6,500 L of biogas per day. Since the installation is not yet in place, a similar methane concentration of 67% is assumed, resulting in 4,355 L of methane daily. Applying the same calorific value, this corresponds to a daily energy yield of approximately 43.33 kWh [147]. Over the course of one year, the resulting energy production is approximately 15,826 kWh. The revenue formula for this scenario is given in Equation 6.5.

$$R_{\text{biogas, t, large}} = P \cdot 15,826 \cdot (0.95)^t \quad (6.5)$$

As with the small-scale analysis, the DCF analysis includes CAPEX, annual OPEX, and inventory holding costs. Attachment H.2 displays the complete cash flow breakdown. The NPV value is calculated in the table as function of biogas price, using Equation 6.6. For the large-scale setup, the total discounted cost of ownership is calculated at TZS 29,309,471 (EUR 9,657.87).

$$\text{NPV} = \sum_{t=1}^{10} (P \cdot 15,826 \cdot (1 - 0.05)^t) - 29,309,471 \quad (6.6)$$

## 6.3.2 Break-even analysis

The break-even analysis aims to determine the minimum price at which the NPV of the system becomes zero. This represents the price point at which the investment neither results in a financial loss nor a profit over the system's lifetime.

### Small-scale

For the small-scale configuration, the total cost of ownership is estimated at TZS 2,943,094, accounting for CAPEX, OPEX and inventory holding cost over a lifespan of 10 years. The break-even cost can be determined setting NPV to zero in Equation 6.4. Given the annual energy output of 246 kWh, the break-even point is reached at a biogas selling price of approximately TZS 1,572 /kWh. At this price, the DCF over the lifespan matches the initial investment exactly.

### Large-scale

The same approach is applied to the large-scale setup. This configuration assumes a significantly higher output of 43.73 kWh per day, resulting in substantially larger revenue.

The total cost of ownership for this setup is calculated at TZS 29,309,471. Using the same discount rate and system lifespan, the break-even price is much lower. The break-

even biogas price is found to be approximately TZS 241 /kWh. This is calculated using Equation 6.6.

### 6.3.3 Biogas pricing

Building on the framework presented previously, the relation between biogas price and economic viability is now further explored. In particular, this subsection examines how the biogas price affects both the NPV and the DPT of the investment. This analysis is crucial in determining the price thresholds under which investment in the system becomes financially attractive.

#### Small-scale

For the small-scale setup, the NPV can be calculated in relation to the biogas price. This relationship is first introduced in Equation 6.4. However, this relation can be simplified. Equation 6.7 shows the simplified relation.

$$\text{NPV} = 1,872 \cdot P - 2,943,094 \quad (6.7)$$

This equation enables an intuitive visual interpretation of how the system's profitability evolves with the biogas price. A graphical representation is provided in Figure 6.1, which shows the trend of NPV over a range of P.

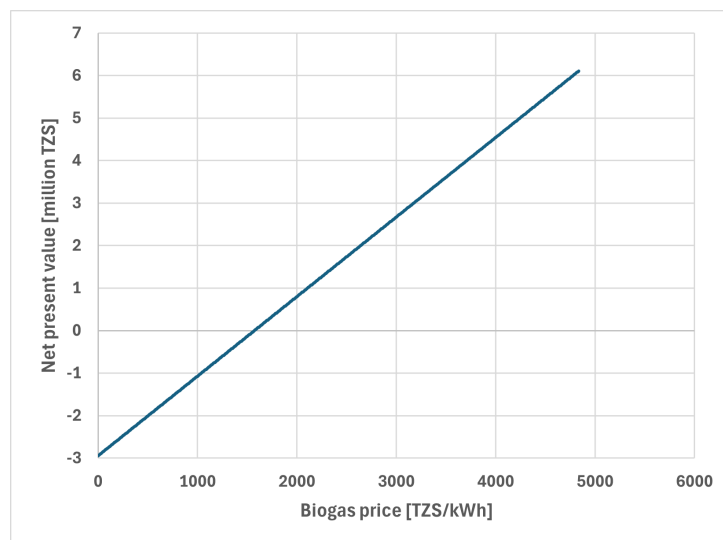


Figure 6.1: NPV in relation to biogas price, for the small-scale setup

As seen in Figure 6.1, the system only becomes profitable when the price is higher than TZS 1,572 /kWh (EUR 0.52 /kWh). If prices below this point are established, outside funding will be necessary. At prices above this, the system becomes profitable. When the price is set to 0, meaning that the biogas is freely given away or used by the investors, the NPV amounts to TZS -2,943,094.

In addition to NPV, the DPT is also a critical indicator, especially in investment decisions. Figure 6.2 shows how DPT changes with the price of biogas of the small-scale purification system.

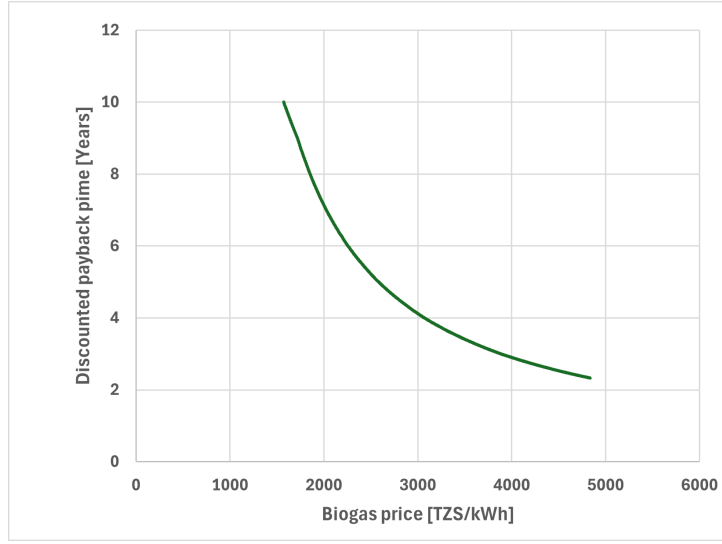


Figure 6.2: DPT in relation to biogas price, for the small-scale setup

Figure 6.2 demonstrates that when the biogas price is doubled to TZS 3,144 /kWh, the DPT extends to 3.88 years. Even with a substantial increase in the price to approximately TZS 5,000 /kWh, the break-even point is not achieved within two years.

### Large-scale

Similar to the small-scale setup, the NPV for the large-scale configuration can be expressed as a function of the biogas price. This relation is derived from Equation 6.6. The simplification is shown in Equation 6.8.

$$\text{NPV} = 121,681 \cdot P - 29,309,471 \quad (6.8)$$

The significantly larger coefficient reflects the much greater energy output and revenue potential of the large-scale system, but the discounted cost of ownership is significantly higher. Figure 6.3 shows how the NPV responds to biogas price variations.

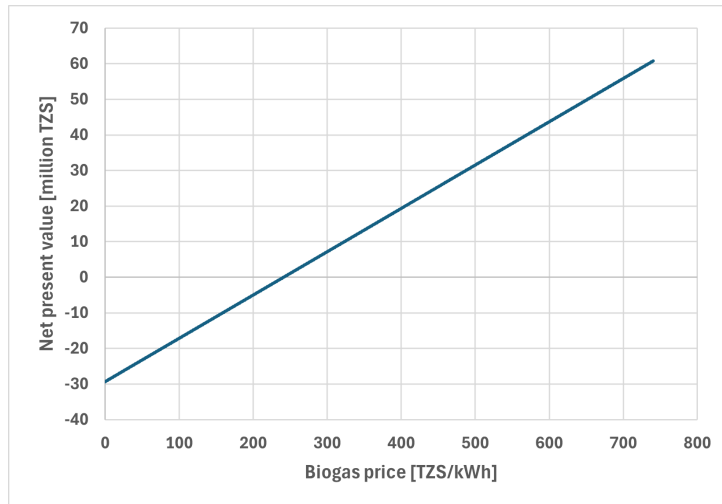


Figure 6.3: NPV in relation to biogas price, for the large-scale setup

In contrast to the small-scale configuration, the break-even price here is only around TZS 241 /kWh (EUR 0.079/kWh). This substantial difference underscores the strong impact of economies of scale on the project's financial feasibility. As the system size increases, the capital expenditures are distributed over a much larger energy output, resulting in a more favorable cost-to-revenue ratio. Consequently, the large-scale setup demonstrates a considerably more efficient conversion of capital into economic return, making it more resilient to fluctuations in biogas pricing.

The same trend is observed in the DPT, shown in Figure 6.4.

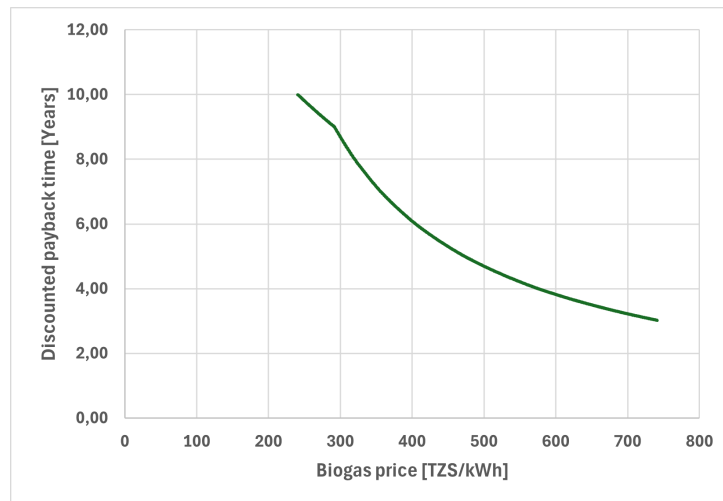


Figure 6.4: DPT in relation to biogas price, for the large-scale setup

Figure 6.4 shows that the payback time curve is less steep compared to the small-scale setup. When the price is doubled to TZS 482/kWh, the DPT decreases to 4.90 years, longer than the value calculated for the small-scale system. In practice, this implies that while economies of scale improve LCOE, achieving equivalent DPT targets requires a proportionally higher energy price for the large-scale configuration.

## 6.4 Comparison with alternatives

This section aims to situate the financial viability of the biogas system by comparing it to commonly available cooking energy sources in rural and Tanzanian households. The alternatives examined are firewood, charcoal, electricity, LPG, and two solar-based configurations: a standalone solar cooking setup and a hybrid solar-biogas system. For each alternative, key economic performance indicators are assessed: LCOE, NPV assuming parity in unit price with biogas and DPT also under equivalent revenue conditions. It is important to note that the standalone solar cooking system and the hybrid solar-biogas configuration are not technically evaluated in this thesis; they are included solely as hypothetical economic alternatives for comparative purposes.

Among these options, the hybrid solar-biogas system stands out as a particularly innovative and promising approach. By integrating solar energy for biogas purification and direct cooking use, this hybrid system maximizes energy utilization and mitigates the limitations inherent in relying solely on solar or biogas individually. This improves economic

viability as well as energy reliability, especially when biogas production or solar energy alone is insufficient to meet demand or achieve profitability.

The section proceeds by first comparing biogas to each conventional fuel alternative, evaluating LCOE, NPV, and DPT. Following this, the standalone solar cooking configuration is examined, including its energy output, cost breakdown, and financial performance. The subsequent subsection then introduces the hybrid solar-biogas system, detailing how the usage of unspent solar energy enhances biogas feasibility. Finally, a comparative LCOE overview summarizes the economic indicators across all options, also discussing their relative advantages and limitations within the rural Tanzanian context.

### **6.4.1 Traditional fuel sources**

This subsection evaluates the economic viability of biogas by comparing it to the most common cooking energy sources in rural Tanzanian contexts. The focus is to determine LCOE, as well as determine the biogas small- and large-scale NPV and DPT assuming parity in unit energy price between each reference fuel and biogas. Cooking efficiencies are not taken into account. However, broader socio-political and environmental considerations such as fuel bans, health impacts and environmental implications will be discussed where relevant.

#### **Firewood**

Firewood remains the predominant cooking fuel in rural Tanzanian households due to its minimal cost [148]. However, extensive reliance on firewood has been linked to severe indoor air pollution and respiratory illnesses [8]. Additionally, unregulated harvesting has led to significant deforestation, from 2001 to 2023, Tanzania lost 3.25 Mha of tree cover, equivalent to about 12% of the country's total forests [149]. In response, the Government of Tanzania's National Clean Cooking Strategy mandates the phase-out of open firewood use in institutions by January 2025 to protect public health and forests [148]. For comparative purposes, the LCOE for firewood is estimated at TZS 34 /kWh (EUR 0.011), based on typical rural market rates [150].

This price of TZS 34 /kWh can be compared to the biogas price of the small-scale system. When setting biogas price to TZS 34 /kWh for the small system, a loss will be made, since this is below the break-even price. At this price, the small-scale biogas system will have an NPV of TZS -2,879,446. This means a substantial loss will be made.

In contrast, if the large-scale system's biogas price is set to the firewood rate, its NPV per plant increases to TZS -25,172,334. Although this figure is nearly ten times greater in absolute terms than the small-scale loss, the large-scale installation produces 65 times more energy, making it significantly more economical per kWh.

#### **Charcoal**

While firewood is the predominant fuel in rural households, charcoal is the most predominant fuel in urban households. Charcoal has been linked to a range of environmental and social problems [151]. As with firewood, Tanzania has an institutional ban to charcoal, with identical deadlines to phase out its use in public and private catering facilities [148]. Charcoal's market price is assumed in a range of TZS 46 to TZS 172 /kWh, based on

local surveys [152]. However, the price of charcoal varies greatly depending on region, in a more rural region, charcoal is less expensive. Since the thesis is based in a rural area, the price will be set at TZS 72 /kWh (EUR 0.024), similar to an earlier rural study [150].

This price of TZS 72/kWh can be compared to the biogas price of the small-scale system. If the biogas from the small system were sold at the same rate of TZS 72/kWh, the system would still operate at a loss, as this remains below its break-even price. At this selling price, the small-scale biogas system would yield a negative NPV of TZS -2,808,309, indicating a significant financial loss.

By contrast, applying the same TZS 72/kWh rate to the large-scale plant yields an NPV of TZS -20,548,475. However, the large-scale installation produces 65 times more energy than the small-scale system, which translates to a substantially higher return per kWh.

## **Electricity**

Grid electricity in Tanzania is predominantly generated from natural gas (73%), with only about 25% contributed by low-carbon sources, mostly hydropower [153]. Moreover, grid reliability remains a challenge, frequent blackouts and lack of infrastructure remain concurrent problems [2]. Typical household prices range from TZS 90 to TZS 100 /kWh (EUR 0.030-0.033) [154], [150]. However, when energy use increases above 75 kWh monthly, the price will increase to TZS 350 /kWh, it is assumed the average rural user will stay below this value.

This price of TZS 100/kWh, can likewise be compared to the biogas price of the small-scale system. If the biogas were sold at this rate, the system would come closer to financial viability but would still be far from break-even. At TZS 100/kWh, the small-scale biogas system would yield a negative NPV of TZS -2,755,893. While this still implies a financial loss, it represents a modest improvement 2% compared to the NPV at a biogas price equivalent to charcoal. When the same is done for the large-scale plant, it has an NPV of TZS -17,141,421.

## **LPG**

LPG is increasingly promoted by the Tanzanian government as a modern cooking fuel [152]. About 5% relies on LPG for cooking, mostly in urban regions [148]. This number is increasing due to government policies, ease of use, and increasing safety awareness. The price for LPG ranges from TZS 17,000 to TZS 25,000 for refilling a 6 kg gas cylinder [148]. For this analysis, a price of TZS 22,700 (EUR 7.48) is used, a price from a local supplier [153]. This converts to TZS 270 /kWh using a calorific density of 13.6 kWh/L.

This price of TZS 270/kWh can likewise be compared to the biogas price of the small-scale system. If the biogas were sold at this rate, the system would still not reach profitability, though the financial outlook would improve slightly. At TZS 270/kWh, the small-scale biogas system would result in an NPV of TZS -2,437,652.

At the LPG equivalent biogas price, the large-scale plant records an NPV of TZS 3,544,264 and reaches a discounted payback time of 9.41 years, just within its 10-year lifespan. While the margin is narrow, this suggests that matching LPG tariffs could make the project financially viable over its intended operating period.



### 6.4.2 Solar energy

In addition to easily available alternative fuels, the solar panels could be used independently. The cost of this is significantly less, as the filtration and digester are no longer needed. This subsection proposes a scenario in which the solar energy supply from the small-scale setup is used for cooking independently. The useful energy output will be estimated, followed by a cost breakdown and an NPV-based economic analysis to assess the viability of this simplified configuration.

#### Energy production

Energy production of the solar energy supply is determined to estimate an LCOE. The total energy of the system during its lifespan is considered. Only the useful energy is considered, the energy that can be effectively delivered to end-use applications after losses in the inverter, PWM controller and wiring. The amount of energy required for cooking varies significantly depending on the type of meal, the number of people served, and the specific appliances used. As illustrated in Figure 6.5, power demands differ widely between electric cooking devices.

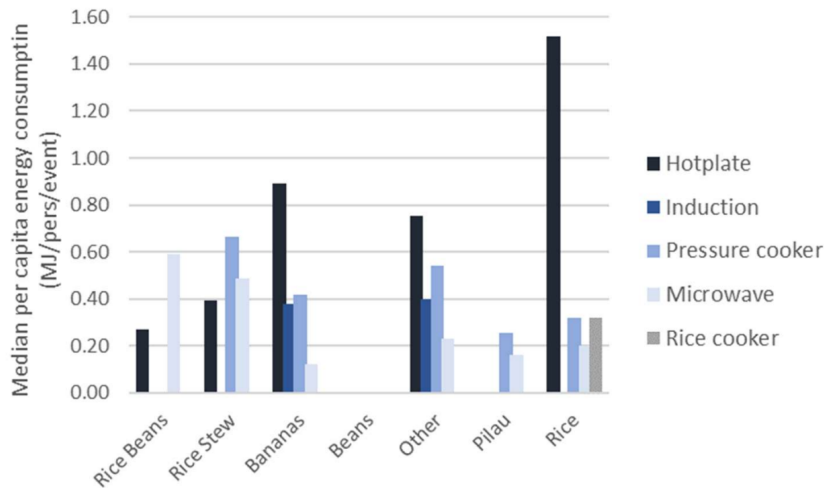


Figure 6.5: Electric energy use per meal, per electric device [128]

As shown in the figure, some dishes require significantly more energy than others. Larger meals or meals for larger households may not be feasible with this setup. When an average is taken, approximately 0.6 kWh is required per cooking event for a household of 4.4 people [128]. Since solar energy is not available in the evening, all evening cooking would need to rely on battery storage. Given a 12 V, 50 Ah battery and a 50% DoD, the usable daily energy storage is limited to 0.3 kWh, without accounting for system losses. This is insufficient to prepare a full meal in the evening. As a result, only one cooked meal per day will be considered. This meal will be cooked at noon, when solar energy is maximum.

For the purpose of this analysis, it is assumed that 0.3 kWh per day can be reliably delivered by the battery. To deliver the full 0.6 kWh needed per day for cooking, an additional 0.3 kWh must come directly from the PV panels. Assuming an overall system efficiency of approximately 75%, this translates to a required solar input of 0.4 kWh/day. In Kimbiji, a daily average DNI of  $4.8 \text{ kWh}/\text{m}^2$  is expected [86]. This corresponds to 4.8

peak sun hours per day, with an installation of 400 Wp, this translates to 1.9 kWh/day. This capacity is more than adequate to meet the projected load demand.

Assuming the battery is discharged daily at 50% DoD, and given an estimated cycle life of 1,000 cycles [136], the battery would last for approximately three years under normal use. In contrast, the solar panels can operate for up to 25 years. According to [155], cooking directly on this small solar system is feasible using experimental insulated cookers. For this analysis, a lifespan of 20 years is assumed, a conservative estimation due to rural conditions and poor maintenance. This lifespan will be further reduced if solar energy is used more extensively for purposes beyond cooking. However, this lies outside the scope of this cost analysis. Given the daily usable energy of 0.6 kWh, this results in a total useful energy output of approximately 4,380 kWh.

However, this is a conservative estimate. In reality, energy availability and cooking feasibility are highly dependent on usage patterns. It is plausible that some breakfast preparation occurs in the morning using direct solar energy, while evening meals might be reheated from stored battery energy. In practice, the useful energy output depends on user behavior, seasonality, and appliance scheduling.

Reliance on solar energy alone introduces vulnerability. On overcast days or during social events with increased demand, the system may be unable to meet user needs. In such cases, supplementary energy sources would be necessary. This highlights a core limitation of using solar PV for cooking in off-grid contexts, it is not solely a matter of average energy sufficiency, but of managing day-to-day variability in both generation and demand. Social aspects of this problem are outside the scope of this study, but are explored in detail in prior work [128].

### **Total cost**

Attachment D.2 provides a detailed breakdown of the capital cost for the standalone solar energy system. The total investment required for the energy supply amounts to TZS 953,750, as established in Section 6.2. The most significant cost drivers are

- the solar panels at TZS 500,000,
- the battery at TZS 170,000,
- the PWM controller at TZS 130,000,
- the inverter at TZS 80,000.

Cooking on low-power solar requires an insulated cooker as proposed in [155]. The original 2018 cost of USD 30, equivalent to approximately TZS 68,310 at the time (exchange rate: 2,277 TZS/USD), is adjusted for Tanzanian inflation to a 2025 estimate of approximately TZS 89,000. This insulated cooker is the only cooking appliance considered in this analysis, as its cost is relatively high compared to common biogas or LPG cookstoves.

Because the solar cooker operates directly from the solar array during daylight hours, this analysis accounts for battery replacement every three years. Panel cleaning and minor maintenance are neglected.

The total capital cost of the solar cooking system, including both the energy supply and the insulated cooker, is therefore estimated at TZS 1,042,750 (EUR 343.60).

### Break even analysis

A break-even analysis was conducted to determine the minimum price  $P$  at which the standalone solar system recovers its total capital investment of TZS 1,042,750 over a 20-year lifespan. Attachment H.3 presents the detailed DCF analysis used in this calculation. Applying the same 5% discount rate as for the biogas systems, the total discounted cost of ownership results in TZS 1,733,447. The NPV can be expressed as a function of the solar energy price, this is done in Equation 6.9.

$$\text{NPV} = \sum_{t=1}^{20} (P \cdot 219 \cdot (0.95)^t) - 1,733,447 = 2,669 \cdot P - 1,733,447 \quad (6.9)$$

In Equation 6.9,  $P$  denotes the price of solar-delivered energy in TZS/kWh, and the coefficient 2,669 represents the present-value factor of the annual 219 kWh of useful energy. Setting NPV to zero and solving for  $P$  yields the break-even price. To recover the capital without profit, the solar energy must be sold at TZS 649 /kWh (EUR 0.21 /kWh). Prices above this threshold generate a positive NPV, while lower prices result in a net loss over the system's lifespan.

### Energy pricing

With a LCOE of TZS 649/kWh, the small-scale solar installation can be compared to the biogas options. The LCOE of biogas from the small-scale system was TZS 1,572/kWh, which is significantly higher than that of the solar system, indicating that solar energy is clearly more cost-effective on a per-kWh basis. However, this solar energy can only be used when the sun is shining, making it less valuable.

If the selling price of solar electricity was set equal to that of biogas from the small-scale system, the financial outcome would be favorable. In this case, the small-scale solar system would achieve a NPV of TZS 2,462,756, indicating a strong return on investment. Furthermore, the payback period would be just 1.5 years, making it an especially attractive option.

However, when the selling price of biogas from the small-scale system was set equal to that of solar electricity, the financial outcome was significantly less favorable. At this price point, the revenue generated would not be sufficient to cover the high production costs of biogas, which has a much higher LCOE of TZS 1,572/kWh. As a result, the small-scale biogas system would operate at a considerable loss, resulting in a NPV of TZS -1,780,577 and a payback period far exceeding the system's expected lifetime.

## 6.4.3 Hybrid solar-biogas

As discussed in Section 6.4.2, the standalone solar energy supply delivers more power at noon than is required to cook a single meal. This surplus opens the possibility of implementing a hybrid system in which solar electricity is used both for cooking and to support biogas purification processes, thus utilizing the energy supply more efficiently.

A hybrid system is particularly attractive when the biogas yield is insufficient to meet cooking demands independently or when the standalone economic viability of small-scale biogas is limited.

### Energy production

The total energy output of the hybrid system comprises the combined contributions of solar electricity and biogas combustion. The daily usable energy output is estimated to be 0.6 kWh from solar energy and 0.67 kWh from biogas, resulting in a total of 1.27 kWh per day. Over the course of a year, this corresponds to approximately 219 kWh from solar and 246 kWh from biogas, yielding a combined annual energy output of 465 kWh.

It is important to note that these two energy sources differ in terms of availability and flexibility. Solar energy is limited to daylight hours and is best suited for cooking at noon or early in the afternoon. In contrast, biogas can be stored and used on demand, including during the evening when solar energy is not available. This complementarity improves the overall utility and reliability of the hybrid system, giving it a functional advantage over single-source systems, apart from comparing total energy output.

### Total cost

The total capital investment for the hybrid system includes the full cost of the solar energy supply, the small-scale biogas system, and a low-power insulated cooker suitable for solar-based cooking. The standalone solar energy system, as detailed in Attachment D.2, has a capital cost of TZS 953,750. The insulated cooker, based on estimates from and adjusted for Tanzanian inflation to 2025, adds an additional cost of TZS 89,000 [155]. The biogas production and purification systems contribute another TZS 1,745,720 in capital costs, as established in Section 6.2. This brings the total capital cost of the hybrid system to TZS 2,699,470.

### Break even analysis

A break-even analysis was conducted to determine the minimum energy price per kWh, denoted as  $P$ , at which the hybrid system recovers its capital investment over its expected lifespan. However, this considers the price of biogas and solar energy to be the same, these can be differed in practice. The analysis assumes a 20-year operational period for the solar system and a 10-year lifespan for the biogas installation, using a uniform discount rate of 5%. Attachment H.3, presents the detailed DCF analysis used in this calculation. The total discounted cost of ownership is TZS 3,678,639. The NPV table assumes the same price per kWh for biogas and solar energy. However, since there are two types of energy output, two different prices can be set. NPV can be expressed as a function of biogas and solar energy price, this is done in Equation 6.10.

$$\text{NPV} = \sum_{t=1}^{10} (P \cdot 245 \cdot (0.95)^t) + \sum_{t=1}^{20} (P \cdot 219 \cdot (0.95)^t) - 3,678,639 = 4,541 \cdot P - 3,678,639 \quad (6.10)$$

In Equation 6.10, the coefficient 4,541 represents the present value factor of the annual 465 kWh of useful energy. Setting NPV to zero and solving for  $P$  yields the break-even

price. To recover capital without profit, the energy must be sold at TZS 810 /kWh (EUR 0.27 /kWh).

### Energy pricing

The LCOE of the hybrid system is estimated at TZS 810 /kWh, which is significantly lower than the LCOE of standalone small-scale biogas, previously calculated at TZS 1,572 /kWh. While large-scale biogas systems are expected to offer much lower LCOE due to economies of scale. The hybrid system thus provides a practical and economical solution for rural energy access, especially where large-scale investments are not possible.

When compared to solar energy generation, the LCOE of hybrid solar-biogas is higher. However, the output energy comes in two forms, electricity during hours of peak sun and biogas to cook with when needed, this makes the setup inherently more valuable.

If the energy selling price of the hybrid system were set equal to that of small-scale biogas, the financial outcome would be highly favorable. Under this scenario, the hybrid system would yield a positive NPV of TZS 3,460,359, indicating solid profitability. The payback period would be about 5 years, making it an appealing option in comparison to small-scale biogas production.

### 6.4.4 LCOE comparison

In this subsection, a comparative analysis of the LCOE is conducted for all previously discussed cooking energy systems. The LCOE provides a straightforward visual comparison of the cost-effectiveness of each system over its lifetime. The size of the investment is not visible in the number for LCOE. These LCOE values include all the costs mentioned in the respective chapter, thus not taking labor costs into account. Put simply, the LCOE of energy would be the cost the community would pay for the alternative source, doing all the work themselves.

#### LCOE excluding cooker efficiency

Figure 6.6 illustrates the LCOE for all the systems under consideration, excluding the efficiency of the cooking appliance itself.

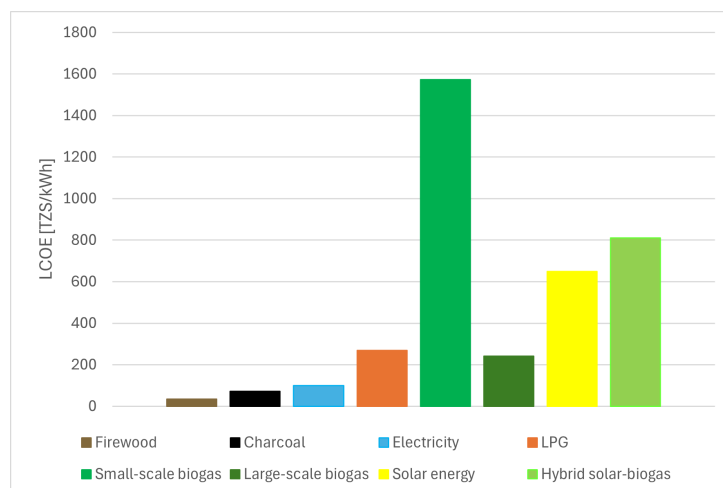


Figure 6.6: LCOE comparison excluding burner efficiency

As shown, traditional fuels such as firewood and charcoal remain significantly cheaper than any of the proposed alternatives in this thesis. Grid electricity also proves to be a cost-effective solution. However, access to electricity in rural communities is limited and unreliable, making it an impractical standalone option [156].

Large-scale biogas installations emerge as a potentially competitive alternative to LPG in terms of cost, especially when considered in the context of a centralized system serving multiple households. This creates an interesting business case, where collective investment by the community could result in an economically viable solution. The calculated LCOE reflects what such an investment would cost per unit of useful energy delivered.

Small-scale biogas systems, on the other hand, perform poorly in terms of cost. The LCOE of these systems is significantly higher than any other option, making them not viable. Nevertheless, there is potential for cost reduction if these systems are operated in hybrid configurations like combining solar energy with biogas production and storage. In such scenarios, the LCOE can be reduced by nearly half, although still not to the level of conventional fuels.

### **LCOE including cooker efficiency**

While the initial comparison considers only the theoretical energy output of the fuel source, a more accurate assessment includes the efficiency with which that energy is transferred to the food. Burner efficiency varies considerably between technologies and plays a crucial role in the actual cost of cooking.

A study conducted in Tanzania [128] determined the intrinsic energy demand required for an average heating event for different fuels. The findings show that charcoal requires approximately 6.0 MJ of energy to cook one meal per person. This is five times more energy than LPG, at 1.2 MJ. Using electricity, only 0.6 MJ was needed per person per meal. For firewood, efficiency also varies significantly on the type of stove used, but is generally lower than that of charcoal stoves. It is assumed that, since firewood cookers are generally less efficient than charcoal cookers, firewood requires 1.5 times more energy than charcoal [157], [158]. This would mean firewood is estimated at 9.0 MJ per person per meal. The amount of energy required per person fluctuates greatly depending on the amount of persons the meal is cooked for, the chosen values are average values. For biogas, a burner efficiency similar to LPG is assumed. Although this is a simplification, the type of stove used remains the dominant factor influencing real-world performance, making the assumption acceptable for this analysis. Figure 6.7 shows the LCOE including burner efficiency, with the LCOE expressed in TZS/event/person.

Figure 6.7 shows the LCOE adjusted for burner efficiency, expressed as TZS per person per average heating occasion, which may include cooking, water heating, or other tasks. Firewood, at TZS 85 /event (EUR 0.028 /event), and charcoal, at TZS 120 /event (EUR 0.040 /event), become substantially more expensive once their low combustion efficiencies are accounted for. In contrast, grid electricity drops to just TZS 17 /event (EUR 0.0056 /event), making it the most economical option by a wide margin, though its limited rural availability remains a problem.

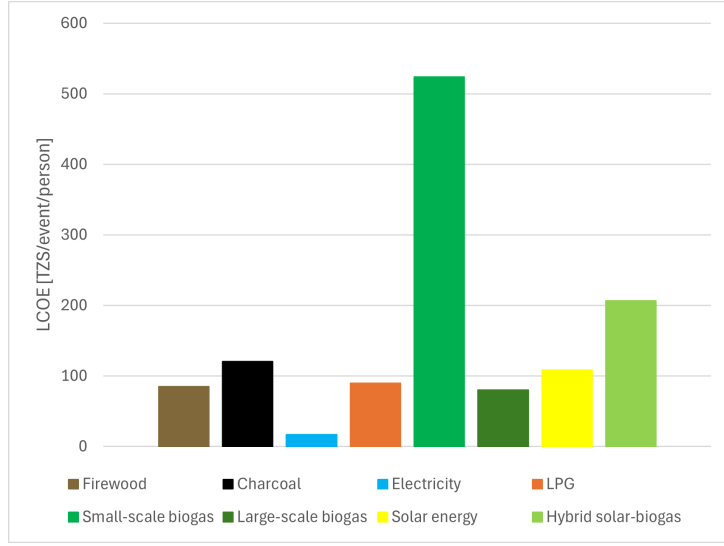


Figure 6.7: LCOE comparison including burner efficiency

Among the thesis's proposed technologies, large-scale biogas now appears highly competitive at TZS 80 /event (EUR 0.026 /event). This value does not only undercut LPG at TZS 90 /event (EUR 0.030 /event), but also undercuts firewood and charcoal now efficiency corrections are applied. Small-scale biogas, by comparison, remains the least cost-effective at TZS 524 /event (EUR 0.17 /event). The hybrid solar-biogas system offers a notable improvement over small-scale biogas, halving its cost to TZS 206 /event (EUR 0.068 /event). Solar energy alone sits just below charcoal at TZS 108 /event (EUR 0.036 /event), illustrating that even standalone solar can challenge traditional solid fuels. However, charcoal remains attractive due to its wide availability, ease of use and tradition, which is not reflected in the LCOE analysis.

## 6.5 Discussion

This section integrates the economic findings of the previous sections and aims to contextualize them in a broader framework of feasibility and implementation. Firstly, the main cost drivers of each configuration are identified and their influence is further explored through a sensitivity analysis. In addition, the implications for scalability, long-term operation, and robustness are examined. Finally, the influence of political and institutional factors on system viability is addressed.

### 6.5.1 Sensitivity analysis

To assess the robustness and reliability of the financial outcomes presented in this study, a sensitivity analysis was conducted for each of the four proposed energy generation setups: small-scale biogas, large-scale biogas, solar energy, and the hybrid solar-biogas configuration. The purpose of this analysis is to identify the most influential parameters on the LCOE and to evaluate the extent to which variations in these parameters could affect the economic feasibility of the systems.

For each configuration, a range of technical and economic parameters was identified. These were varied with realistic ranges. All capital and operational cost components

were varied by  $\pm 30\%$  to reflect uncertainty in market prices and potential cost reduction opportunities. The discount rate was analyzed in a range between 3% and 7%, reflecting both conservative and optimistic financing scenarios. Similarly, both system lifespan and energy output (biogas or electricity) were subjected to a  $\pm 30\%$  variation, capturing potential degradation, operational inconsistency, or performance improvements.

For every scenario, the LCOE was recalculated with the modified input values and compared to the baseline LCOE, as calculated in the previous chapters. The resulting differences are presented as the magnitude of LCOE variation ( $\Delta\text{LCOE}$ ) values. It is important to note that the burner efficiency is excluded from these calculations to allow for a fair comparison between setups.

## Small-scale

The small-scale biogas setup was analyzed to determine the impact of key cost and performance parameters on the LCOE, with a baseline LCOE of TZS 1,572 /kWh (EUR 0.52 /kWh). This configuration, intended for decentralized rural implementation, is sensitive to various factors that are strongly influenced by local construction practices, operational consistency, and equipment sourcing.

The parameters selected for variation include the costs of  $\text{CO}_2$  absorbent materials, battery replacement, purification infrastructure, energy supply, and the digester itself. Additionally, the system lifespan, discount rate, and raw biogas production were varied. The results of this analysis are presented in Figure 6.8, which illustrates the  $\Delta\text{LCOE}$  corresponding to each varied parameter.

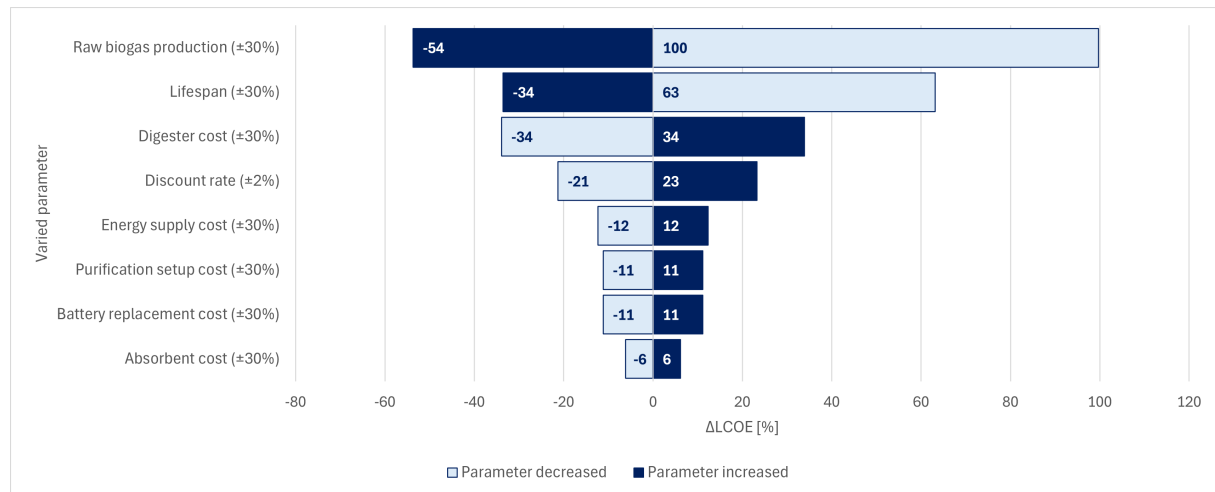


Figure 6.8: Sensitivity analysis of the small-scale biogas generation setup, showing relative variation in LCOE

The parameter with the most significant impact was found to be raw biogas production. A 30% increase in biogas yield results in a considerable reduction of the LCOE from TZS 1,572 /kWh to approximately TZS 1,239 /kWh, whereas a 30% decrease raises the LCOE to TZS 2,191 /kWh. This highlights the critical importance of consistent and sufficient reactor feeding, which in turn depends on the reliability of community engagement and availability of feedstock. However, this analysis does not account for the potential increase in digester size or cost that may be required to accommodate higher gas yields.



The second most influential factor is the lifespan of the system. Increasing the lifespan by 30% significantly improves the LCOE, while a reduced lifespan leads to a clear economic penalty. This finding underscores the need for proper system maintenance and long-term sustainability. In the context of this project, effective knowledge transfer becomes crucial. The success of the project depends on local users being equipped with the technical skill and understanding to ensure optimal operation and upkeep over time.

Another key parameter is the cost of the digester. In the current design, digester components were sourced through Ardhi University, which may not reflect typical market rates. It is assumed that commercial or rural market procurement could result in lower costs. A 30% reduction in digester cost, for instance, would lower the LCOE to approximately TZS 1,321 /kWh, indicating that sourcing optimization has tangible benefits for system affordability.

Conversely, several other parameters, such as the costs of the energy supply system, purification infrastructure, battery replacement, and  $CO_2$  absorption, demonstrated only marginal influence on the LCOE within the analyzed range. Their limited impact suggests that the design and budgeting of the current system were already optimized for cost-effectiveness, leaving little room for further economic improvement in this area.

Overall, the sensitivity analysis reveals that the small-scale biogas system's economic viability relies primarily on maximizing raw biogas output and extending system lifespan. Both depend significantly on local engagement. In contrast, reducing maintenance-related operational costs appears to have a negligible effect. In conclusion, future optimization efforts should prioritize capital cost reductions and ensure consistent operational performance, rather than focusing on maintenance expenditures.

## Large-scale

The large-scale biogas configuration, designed to serve a greater number of households and benefit from economies of scale, was subjected to a similar sensitivity analysis to understand how technical and financial parameters affect its LCOE. This system builds on the principles of the small-scale setup but involves higher capital investment and more biogas production. The baseline LCOE for this setup is TZS 214 /kWh (EUR 0.071 /kWh), which is determined in earlier chapters.

The parameters evaluated include discount rate, battery replacement cost,  $H_2S$  absorbent cost, digester cost, energy supply cost, biogas purification cost, raw biogas production, and system lifespan. Figure 6.9 will show the resulting  $\Delta$ LCOE values, in relation to the changes in the aforementioned parameters.

The sensitivity analysis highlights eight parameters, four of which dominate the biogas break-even price.

The most influential factor is raw biogas production. Increasing the biogas production by 30% would reduce the LCOE to TZS 214 /kWh. However, achieving such increase would pose a significant challenge.

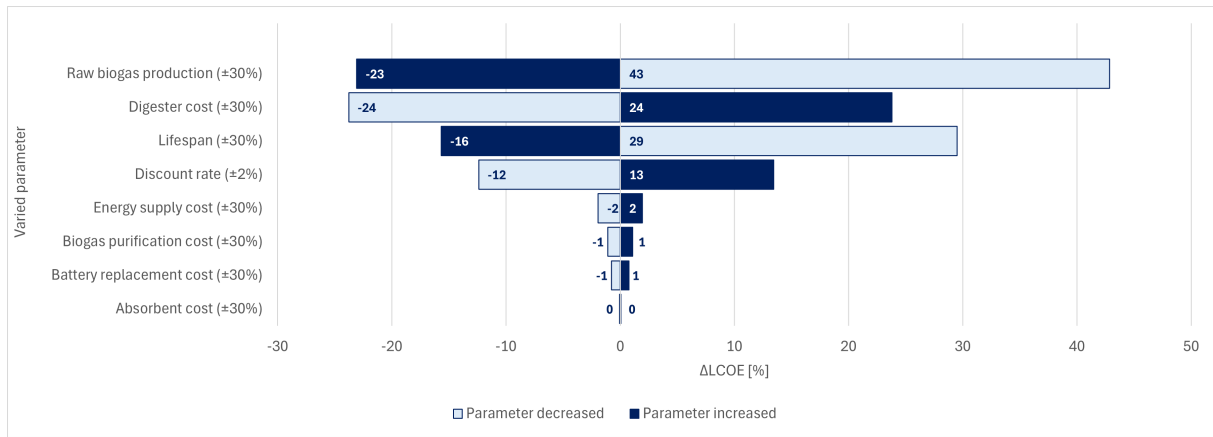


Figure 6.9: Sensitivity analysis of the large-scale biogas generation setup, showing relative variation in LCOE

The capital cost of the digester ranks second in importance. Because the current cost estimate relies on preliminary data, the actual LCOE becomes uncertain. Further studies or an actual implementation should determine a more reliable capital cost for the digester.

The discount rate also shapes project economics, but its scope for adjustment is limited, making it less important.

Lifespan has a significant impact, especially when compared to other costs including the energy supply, biogas purification cost, batter replacement and absorbent costs. From this, a conclusion can be drawn that investing in higher-quality, more durable components can, despite their greater upfront cost, lower the LCOE.

## Solar energy

The solar energy configuration is distinct from the biogas-based setups in that it directly generates electricity from solar panels, rather than relying on gas combustion. This system was primarily included to evaluate the potential of a cleaner, lower-maintenance alternative or complement to biogas in rural electrification. The sensitivity analysis for this configuration helps identify which technical and financial parameters most influence its economic viability, as expressed through the LCOE.

The base LCOE for this system, calculated in 6.4.2, is TZS 649 /kWh (EUR 0.21 /kWh). To assess the robustness of this number, the sensitivity analysis varied the parameters. These include discount rate, battery replacement cost, energy supply cost, usefull electrical output, and system lifespan. The results are presented in Figure 6.10, which shows how each of these variables affects  $\Delta$ LCOE relative to the baseline LCOE of TZS 649 /kWh.

The analysis reveals that the most influential parameter is the useful electrical energy output. A 30% increase in electrical usefull energy reduces the LCOE to TZS 499 /kWh. This improvement illustrates how significantly the cost-effectiveness of the solar system is tied to maximizing output. Conversely, a 30% decrease in useful output pushes the LCOE toward TZS 898 /kWh, significantly undermining its economic viability.

Battery replacement cost and energy supply cost, are also significant factors. The lifespan of the solar system, assumed to be approximately 20 years in the base case, also plays a significant role. Extending the lifespan by 30% decreases the LCOE notably, while

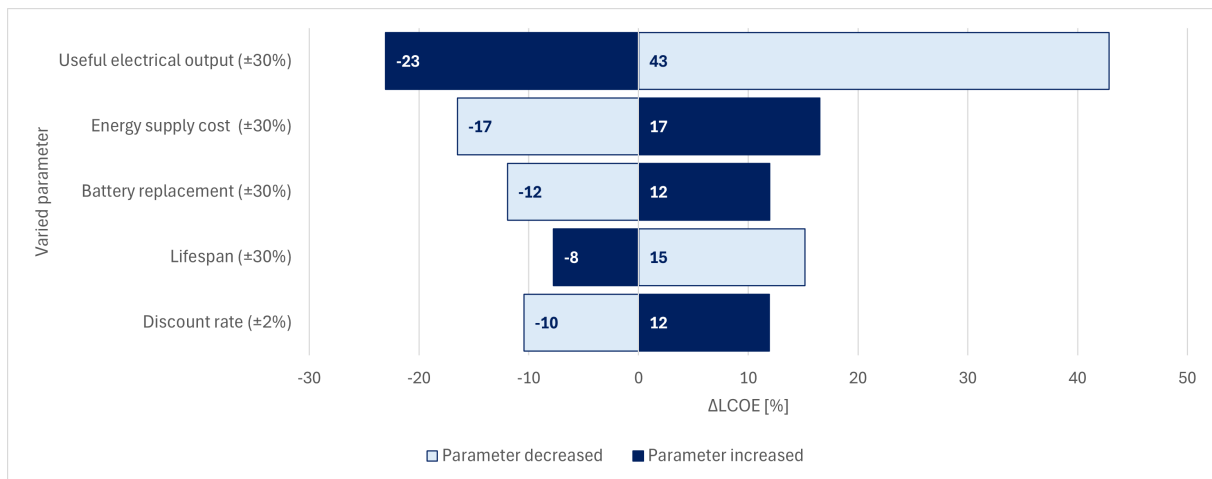


Figure 6.10: Sensitivity analysis of the solar energy generation setup, showing relative variation in LCOE

shortening it increases the cost. However, reducing or increasing this lifespan is not straightforward. Discount rate increases in relevance relative to the previous sensitivity analyses, due to the longer lifespan. In summary, the sensitivity analysis confirms that the solar setup's LCOE is highly dependent on the effective conversion and utilization of sunlight into electricity.

### Hybrid solar-biogas

The hybrid solar-biogas system integrates the benefits of both standalone setups, combining solar power generation with biogas production and combustion. This approach has a lower LCOE than the small-scale biogas production. However, it also increases system complexity, leading to a greater number of parameters affecting economic viability.

The base LCOE for this system, as established in 6.4.3, was TZS 810 /kWh (EUR 0.27 /kWh). To investigate the robustness of this number, 10 key parameters were varied:  $CO_2$  absorbent cost, purification setup cost, battery replacement cost, solar system lifespan, energy supply cost, biogas system lifespan, raw biogas production, digester cost, discount rate, and useful electrical output. Figure 6.11 presents the results, plotting the resulting  $\Delta$ LCOE values.

Among all parameters, the most dominant is the useful electrical output. A 30% increase in net electricity production reduces the LCOE to TZS 689 /kWh. This impact surpasses that of raw biogas production because the solar component of the hybrid system generates more usable energy over time, given its longer expected lifespan. Therefore, ensuring maximal electricity usage is critical.

The discount rate emerges as the second most influential factor. While it cannot be directly controlled, its effect is magnified in this configuration due to the extended lifespan. A higher discount rate reduces long-term benefits, especially those of the solar panels. Capital costs also remain central to the LCOE outcomes. These include the digester cost, purification setup cost, and energy supply system cost. Sourcing them affordably is vital to economic viability.

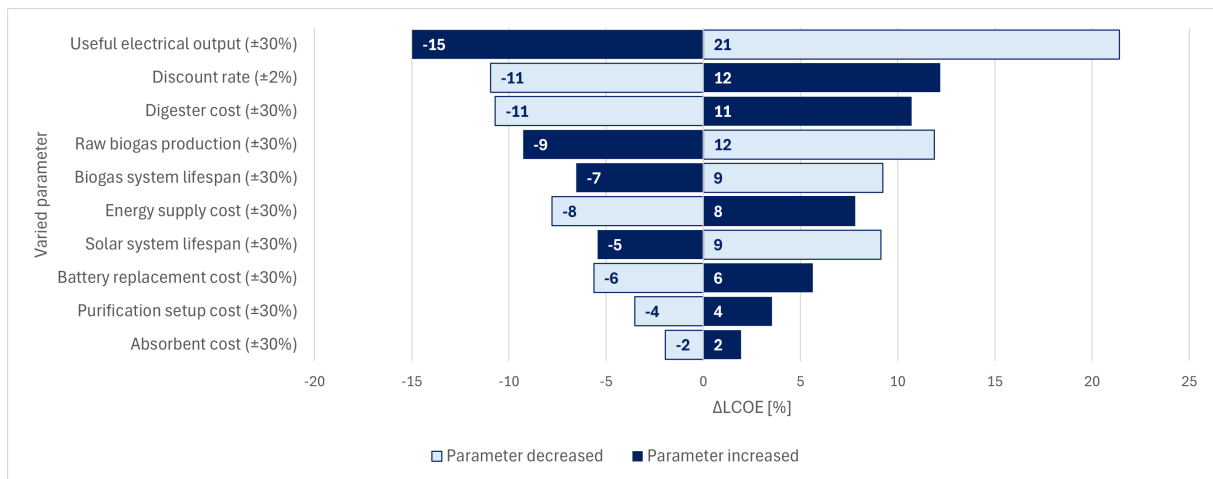


Figure 6.11: Sensitivity analysis of the hybrid energy generation setup, showing relative variation in LCOE

System lifespan is another notable factor. Both the biogas and solar lifespans were varied independently, and the biogas subsystem lifespan proved more significant. The biogas system is also more prone to premature failure, again underlining the importance of operator knowledge and proper maintenance.

Other parameters, such as  $CO_2$  absorbent cost and battery replacement cost, showed relatively minor influence on the LCOE. Although they contribute to the total operating cost, their absolute values are low compared to total capital expenses and energy output. Nonetheless, these costs should still be optimized where possible.

In conclusion, the sensitivity analysis suggests that efforts to enhance electrical and biogas outputs and reduce capital costs, especially for the digester, offer the greatest leverage in lowering the LCOE.

## 6.5.2 Scalability

Scaling the system introduces both opportunities and limitations. Economies of scale reduce the relative cost per unit of gas purified and compressed, thereby improving feasibility. Large-scale systems benefit from lower specific CAPEX and OPEX and allow for more sophisticated purification setups, enabling access to commercial markets.

However, scaling also implies centralization. Centralized systems face logistical challenges related to feedstock collection and distribution. Moreover, in community-based contexts, mobilizing the capital required for large-scale deployment remains difficult. Risk aversion, limited financial literacy, and low access to credit hinder collective investment, despite potential long-term benefits.

In addition to financial and logistical barriers, knowledge transfer presents a significant hurdle. If a community aims to construct a large-scale biogas purification system, the technical know-how must first be made accessible. This presents challenges in rural areas where engineering expertise and training opportunities are limited. Without targeted educational support and external guidance, local construction and operation of such a system may not be feasible.

Furthermore, many of the required components for large-scale purification systems are not readily available in rural areas and must be sourced from urban centers such as Dar es Salaam. This dependency introduces additional transport costs and logistical issues, further increasing the system's overall cost and complexity.

Thus, while large-scale systems may appear more profitable in theory, their practical implementation in rural Tanzanian settings remains significantly more complex than smaller, modular alternatives. However, the economic analysis conducted in this study indicates that the current small-scale configurations are not financially viable in their present form. This highlights the need to either address the practical challenges of implementing large-scale systems or further optimize the small-scale setups to improve their cost-effectiveness and long-term sustainability.

### 6.5.3 Political influences

Governments in sub-Saharan Africa have long recognized that household energy choices are sensitive to public policy instruments. Urbanization in most of these countries has led to a rise in charcoal consumption as traditional firewood use declines [159]. In response, policymakers have deployed a variety of fiscal and regulatory tools, such as subsidies, taxes, bans and exemptions, to try and shift demand toward cleaner and cheaper alternatives [160].

In Tanzania specifically, national and local governments have enacted a range of policy interventions in an effort to curb charcoal dependency and protect forest resources. Government-led initiatives have been documented to promote alternative cooking fuels by providing subsidies for LPG [152]. Despite these efforts, charcoal remains the dominant urban fuel source due to its perceived affordability and availability [148].

This project proposed a setup which could provide energy for 57 urban households. This setup would require total discounted cost of ownership of TZS 2,943,094 to cover CAPEX, OPEX and inventory holding costs. If the price were set similar LPG, there would even be a slight profit margin, the total profits would be TZS 3,544,264. Because a biogas system requires a high initial investment but has low operating costs, it is well-suited for subsidies. A one-time subsidy can lead to a financially sustainable biogas project from which the community can benefit over the entire lifespan of the installation.

Figure 6.7 indicates that biogas supplies energy at TZS 80 per heating event, while charcoal would have a price of TZS 120 for these heating events. This would indicate that biogas on a larger scale can even be more cost efficient for communities than charcoal.

These results imply that a scaled subsidy framework, complemented by targeted social awareness campaigns, could facilitate a shift away from both charcoal and LPG toward biogas in urban fuel markets. Crucially, even in the absence of direct government funding, community-led installations can be cost-effective. However, this would require collaborations. Formal collaboration among local government agencies, academic institutions, and technical service providers will be needed for both the viability and long-term sustainability of community-scale biogas programmes.

# Chapter 7

## Conclusion

This thesis presented the design, implementation, and evaluation of a self-sustaining, small-scale biogas upgrading and distribution system tailored for rural contexts in Tanzania, with a specific focus on Kimbiji. Here, at a test site from Ardhi University, a fixed-dome anaerobic digester serves as the experimental platform. Originally designed for a biogas output of 6,500 L per day, the system was downscaled to a prototype capable of producing 100 L per day. The primary objective was to upgrade and distribute raw biogas, initially composed of approximately 64%  $CH_4$ , 35%  $CO_2$ , and 260 ppm  $H_2S$ , to a composition of at least 75%  $CH_4$  with  $H_2S$  levels reduced to 5 ppm or less.

An extensive literature review identified water scrubbing and  $Ca(OH)_2$  absorption as viable methods for  $CO_2$  removal. Absorption was also suitable for  $H_2S$  purification. To facilitate distribution, a reciprocating compressor can be used to compress the gas into an LPG cylinder. The review also evaluated various off-grid power solutions and determined that a solar array combined with lead-acid batteries was the optimal choice.

Subsequently, two complete upgrading system concepts were designed, one based on water scrubbing and the other on chemical absorption. These concepts were then developed into a comprehensive design, comprising four subsystems: pre-processing, gas upgrading (water scrubbing or  $Ca(OH)_2$  absorption), post processing, and energy supply. For  $H_2S$  removal,  $Fe_2O_3$ , steel wool, rusted steel wool, and activated carbon were indicated as promising absorbents. In the design, local availability of parts and low cost are important factors to increase the lifespan of the system.

At Ardhi university these designs were translated into a working test setup for comparison and evaluation. For  $H_2S$  removal, the most efficient  $H_2S$  absorption material was found to be  $Fe_2O_3$ , reducing the  $H_2S$  level to 3 ppm. The rusted steel wool, capable of reducing the  $H_2S$  levels to 7 ppm, was selected as the most suitable solution as it can be obtained from any rusted steel and thus has a negligible cost. A leak in the university digester during  $CO_2$  scrubbing permitted air to enter the system, comprising up to 15% of the resulting biogas mixture. When accounting for this leak,  $Ca(OH)_2$  absorption had the most stable removal efficiency, averaging at 61%  $CO_2$  reduction. Water scrubbing had a rising efficiency as the pressure increased throughout the process, starting from a 0% removal efficiency and rising to 60 % at 5 bar, reaching 16 %  $CO_2$ . At 5 bar this setup failed.

A refrigerant compressor was used at the setup due to its wide availability, relatively low cost, and leak free design. In the setup, the compressor serves as the driving force, forcing gas through the absorption and water scrubbing setup and into an LPG tank. A small LPG tank requires 112 L of unfiltered biogas to be filled and can supply a household with one average heating occasion, these include meals, boiling water or others. For this setup, manuals and instruction videos were provided to assist local students in the operation, development, and optimization of this setup.

For the Kimbiji setup, rusted steel wool and  $Ca(OH)_2$  absorption were selected. This setup includes the power supply that consists of a 400 Wp solar array connected to a 50 Ah 12 V lead-acid sealed battery, a 60 A PWM controller and a 600 W inverter. This setup was able to filter out 68 vol%  $CO_2$ , and was able to reduce  $H_2S$  levels to 2 ppm. This setup, costing TZS 1,386,470 (EUR 456.86) in total, is fully made up of locally available components, sourced from local markets and stores. The most significant challenge in the current design is the high inrush current drawn by the compressor, which occasionally prevents the system from powering on. Secondly, if the biogas composition changes, the amount of absorbent required might also differ, without frequent biogas quality analysis, this proves difficult to estimate.

A large-scale Kimbiji setup is also presented in this work. This setup, capable of processing 6,500 L of unpurified biogas, would employ water scrubbing and granulated  $Fe_2O_3$  absorption for  $CO_2$  and  $H_2S$  removal respectively. This setup would have a CAPEX of TZS 26,181,130 (EUR 8,627.04), an OPEX of TZS 104,508 (EUR 34.44) and an inventory holding cost of TZS 5,813,500 (EUR 1,915.63). In comparison, the current, small-scale Kimbiji setup has a CAPEX of TZS 2,222,595 (EUR 732.38), an OPEX of TZS 87,978 (EUR 28.99) and an inventory holding cost of TZS 124,000 (EUR 40.86). These prices include digester costs, which makes up a significant portion of the CAPEX for both setups.

Chapter 6 demonstrates that while the proposed small-scale biogas purification and compression system offers technical viability, it lacks the financial viability needed for sustainable deployment. Using a DCF framework with a 5% discount rate over a 10-year horizon, the NPV analysis reveals that the setup requires a break-even price of approximately TZS 1,572 /kWh (EUR 0.52 /kWh). In contrast, the large-scale design dramatically improves economics, leveraging economies of scale to lower per-unit capital and operating costs. The break even price of the large-scale biogas is TZS 241 /kWh (EUR 0.079 /kWh).

When compared to alternative energy sources using LCOE, large-scale biogas outperforms traditional fuels such as firewood, charcoal and LPG, after adjusting for cooking efficiency. Alternatively, cooking directly from solar panels could achieve a LCOE of TZS 621/kWh (EUR 0.20 /kWh), outperforming the small-scale biogas setup. Eventually, the solar setup can be combined with the small-scale biogas setup, this could provide a LCOE of TZS 810 /kWh (EUR 0.27 /kWh), significantly improving the value of the small-scale setup.

The sensitivity analysis identifies raw biogas production and system lifespan as the primary cost drivers for both small- and large-scale biogas systems. A 30% increase in gas production results in an LCOE reduction of 11% for the small-scale setup and 21% for

the large-scale system. Conversely, a 30% reduction in system lifespan leads to LCOE increases of 12% and 21%, respectively. Building on the design, implementation, and validation phases carried out at both the university and in Kimbiji, several promising avenues for further research and development become apparent. This section focuses on the most crucial aspects that can be further researched or developed. Advancing these areas will enhance both technical efficiency, community-level impact, and economical feasibility.

## 7.1 Future work

The current setup at the Kimbiji site can be further optimized to reduce costs and improve system robustness. One avenue is to replace the components prior to the  $H_2S$  purification stage. These pretreatment materials should be resistant to degradation in environments with high  $H_2S$  concentrations, thus prolonging lifespan and improving overall reliability.

Rusted steel wool has proven to be an effective low-cost adsorbent for  $H_2S$  removal, successfully reducing  $H_2S$  concentrations to as low as 2 ppm, well below required thresholds. Future research should investigate the adsorption capacity, degradation rates, and performance of rusted steel sourced from waste. Additionally, optimizing the geometry of the absorption unit could further enhance flow distribution, efficiency, and performance.

The current  $CO_2$  absorption and water scrubbing systems also present opportunities for optimization. Future studies should focus on determining the optimal column length, diameter, and flow rate for the absorption setup. In the water scrubbing system, the future work is replacing the existing pump with a more suitable unit capable of delivering the required water flow and pressure. Moreover, in both setups, the introduction of turbulence-inducing elements and optimization of the scrubbing column dimensions could improve gas-liquid contact and overall efficiency.

The existing power supply and battery system at the Kimbiji site are functional but face reliability challenges, particularly due to the high inrush current drawn by the compressor. Future work should explore methods to improve power reliability, such as placing a car battery in parallel to the current battery, or incorporating a resistor during the start of the system. In addition to this, the incorporation of a custom-built MPPT controller can improve efficiency and cost-effectiveness.

Should a full-scale digester be constructed, the proposed purification setup can be implemented and evaluated under real-world operating conditions to assess system robustness and purification quality. Once operational, actual cost figures can be used to update and improve the economic assessment.

The economical viability of the system can be further explored. The ideal biogas production scale, taking into account economic feasibility and community size. In addition to this, further research should go into feedstock collection feasibility and costs, as this has not been addressed in the current economical analysis. The feasibility of feedstock collection will largely depend on scale. A more in-depth analysis is recommended to further assess potential revenue from biomass sludge and  $CaCO_3$  by-products.

Future work could also look into distribution possibilities. This thesis proposed compression for the technical feasibility of distribution. However, the actual implementation of



a distribution network is still to be investigated. This includes evaluating infrastructure requirements, transport methods, safety considerations, and community-level coordination.

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# Appendix A

## Overview of selected components of the university setup

The initial investment cost of the water scrubbing setup is TZS 683,300 (EUR 225.16) and the initial investment cost of the absorption setup is TZS 488,540 (EUR 160.98). These totals exclude the energy supply as this is not representative of an independent power supply using solar panels. From this cost the cost of the mounting hardware was excluded as the setup can also be hung against a wall directly.

### A.1 Preprocessing

Table A.1 gives the bill of materials (BOM) of the university setup. A picture of all the parts in the setup is given, as well as the price in TZS.

Table A.1: University setup BOM: preprocessing

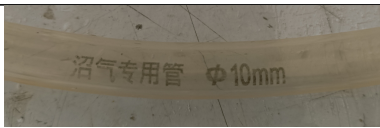
| Nr.                    | Product               | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 1                      | Biogas hose<br>Ø10 mm |  | 1,000                    | 2 m    | 2,000                   |
| 2                      | Biogas valve          |  | 3,000                    | 2      | 6,000                   |
| Continued on next page |                       |                                                                                      |                          |        |                         |

Table A.1 – continued from previous page

| Nr.                    | Product                         | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|---------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 3                      | Pressure gauge, 0-16 kPa        |    | 10,000                   | 1      | 10,000                  |
| 4                      | Moisture trap                   |   | 5,000                    | 1      | 5,000                   |
| 5                      | Ungrooved PP fiber water filter |  | 30,000                   | 1      | 30,000                  |
| 6                      | Compressor<br>ADW43             |  | 141,000                  | 1      | 141,000                 |
| Continued on next page |                                 |                                                                                      |                          |        |                         |

Table A.1 – continued from previous page

| Nr.                    | Product                              | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|--------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 7                      | Garden hose<br>Ø10 mm                |    | 1,280                    | 10 m   | 12,800                  |
| 8                      | Brass nipple 15/16<br>inch to Ø10 mm |   | 11,800                   | 2      | 23,600                  |
| 9                      | Clamps                               |  | 410                      | 13     | 5,330                   |
| 10                     | T-connector, plas-<br>tic, Ø10 mm    |  | 2,000                    | 1      | 2,000                   |
| Continued on next page |                                      |                                                                                      |                          |        |                         |



Table A.1 – continued from previous page

| Nr. | Product                         | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|---------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 11  | Iron wool (15 g) <sup>1</sup>   |    | 500                      | 6      | 3,000                   |
| 12  | Iron oxide (750 g) <sup>1</sup> |   | 5,000                    | 1      | 5,000                   |
| 13  | Activated carbon <sup>1</sup>   |  | 35,000                   | 1 kg   | 35,000                  |

Total cost of the preprocessing setup is TZS 237,730 (EUR 78.34), excluding the cost of the  $H_2S$  absorbent.

<sup>1</sup> Only one of these can be used at the same time.

## A.2 Water scrubbing setup

Table A.2 gives an overview of the BOM of all the parts needed for the water scrubbing phase of the setup.

Table A.2: University setup BOM: water scrubbing setup

| Nr.                    | Product                                    | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|--------------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 14                     | PVC water pipe 2 inch, grade C             |    | 7,500                    | 1.36 m | 10,200                  |
| 15                     | PVC-U, PN16 end-cap 2 inch                 |   | 5,000                    | 2      | 10,000                  |
| 16                     | PVC threaded female socket Ø26 to 3/4 inch |  | 2,000                    | 4      | 8,000                   |
| Continued on next page |                                            |                                                                                      |                          |        |                         |

Table A.2 – continued from previous page

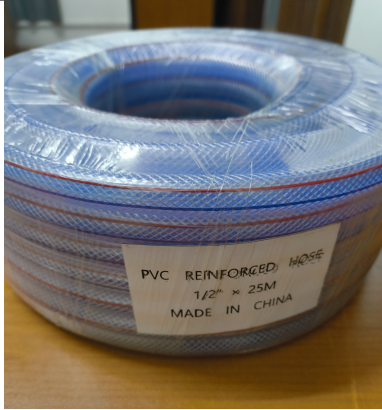
| Nr.                    | Product                            | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 17                     | Brass nipple 3/4<br>inch to Ø10 mm |    | 5,000                    | 4      | 20,000                  |
| 18                     | PVC glue, PVC-U<br>PN16            |   | 15,000                   | 1      | 15,000                  |
| 19                     | Pressure washer set                |  | 220,000                  | 1      | 220,000                 |
| 20                     | Garden hose<br>Ø10 mm              |  | 1,200                    | 0.5 m  | 600                     |
| Continued on next page |                                    |                                                                                      |                          |        |                         |

Table A.2 – continued from previous page

| Nr. | Product                       | Picture                                                                                                                    | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|-------------------------------|----------------------------------------------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 21  | Garden hose connector         |                                          | 7,100                    | 1      | 7,100                   |
| 22  | Clamps                        |                                         | 410                      | 6      | 2,460                   |
| 23  | Water jug 18 L                |                                        | /                        | 1      | /                       |
| 24  | High pressure air hose Ø10 mm |  | 6,000                    | 2 m    | 12,000                  |
| 25  | Biogas valve                  |                                        | 3,000                    | 1      | 3,000                   |

The total cost of the water scrubbing setup is TZS 308,360 (EUR 101.61).



## A.3 Absorption setup

Table A.3 gives an overview of the BOM of all the parts used in the absorption setup.

Table A.3: University setup BOM: absorption setup

| Nr.                    | Product                                       | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 26                     | PVC water pipe 2 inch, grade C                |    | 7,500                    | 1.7 m  | 12,750                  |
| 27                     | PVC-U, PN16 end-cap 2 inch                    |   | 5,000                    | 2      | 10,000                  |
| 28                     | PVC threaded female socket Ø26 mm to 3/4 inch |  | 2,000                    | 2      | 4,000                   |
| Continued on next page |                                               |                                                                                      |                          |        |                         |

Table A.3 – continued from previous page

| Nr.                    | Product                         | Picture                                                                                                                   | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|---------------------------------|---------------------------------------------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 29                     | Brass nipple 3/4 inch to Ø10 mm |                                         | 5,000                    | 2      | 10,000                  |
| 30                     | PVC glue, PVC-U, PN16           |                                        | 15,000                   | 1      | 15,000                  |
| 31                     | PVC-valve, 2 inch               |                                       | 45,000                   | 1      | 45,000                  |
| 32                     | High pressure air hose Ø10 mm   |  | 6,000                    | 2 m    | 12,000                  |
| 33                     | Clamps                          |                                       | 410                      | 4      | 1,640                   |
| Continued on next page |                                 |                                                                                                                           |                          |        |                         |

Table A.3 – continued from previous page

| Nr. | Product                         | Picture                                                                            | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|---------------------------------|------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 34  | bag of industrial<br>$Ca(OH)_2$ |  | 1,400                    | 150 g  | 210                     |

The total cost of the absorption setup is TZS 110,600 (EUR 36.44). This excludes the needed  $Ca(OH)_2$  at TZS 1,400 /kg (EUR 0.46 /kg).

## A.4 Post processing

Table A.4 gives a BOM overview of all the parts used in the post processing.

Table A.4: University setup BOM: post processing

| Nr.                    | Product                           | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 35                     | Pressure gauge, 0-14 bar          |    | 20,000                   | 1      | 20,000                  |
| 36                     | Pressure gauge, 0-16 kPa          |   | 10,000                   | 1      | 10,000                  |
| 37                     | Brass nipple 15/16 inch to Ø10 mm |  | 11,800                   | 2      | 23,600                  |
| Continued on next page |                                   |                                                                                      |                          |        |                         |



Table A.4 – continued from previous page

| Nr.                    | Product                            | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 38                     | Brass nipple 3/4<br>inch to Ø10 mm |    | 5,000                    | 1      | 5,000                   |
| 39                     | Brass nipple 3/4<br>inch to Ø8 mm  |   | 5,000                    | 1      | 5,000                   |
| 40                     | Biogas valve                       |  | 3,000                    | 1      | 3,000                   |
| Continued on next page |                                    |                                                                                      |                          |        |                         |

Table A.4 – continued from previous page

| Nr.                    | Product               | Picture                                                                             | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------|-------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 41                     | Brass valve PN20      |   | 7,000                    | 1      | 7,000                   |
| 42                     | Water filter, 125 psi |  | 18,000                   | 1      | 18,000                  |
| Continued on next page |                       |                                                                                     |                          |        |                         |

Table A.4 – continued from previous page

| Nr.                    | Product                      | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 43                     | T-connector, plastic, Ø10 mm |    | 2,000                    | 1      | 2,000                   |
| 44                     | Brass T-connector 8 mm       |    | 2,000                    | 2      | 4,000                   |
| 45                     | LPG valve                    |  | 15,000                   | 1      | 15,000                  |
| 46                     | Clamps                       |  | 410                      | 21     | 8,610                   |
| Continued on next page |                              |                                                                                      |                          |        |                         |

Table A.4 – continued from previous page

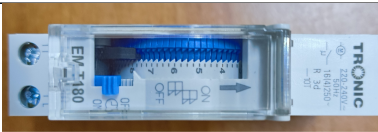
| Nr. | Product                          | Picture | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|----------------------------------|---------|--------------------------|--------|-------------------------|
| 47  | High pressure air<br>hose Ø10 mm |         | 6,000                    | 1 m    | 6,000                   |
| 48  | High pressure air<br>hose Ø8 mm  |         | 4,000                    | 3 m    | 12,000                  |
| 49  | Biogas hose,<br>Ø10 mm           |         | 1,000                    | 1 m    | 1,000                   |
| 50  | Empty LPG tank,<br>15.6 kg       |         | 20,000                   | 1      | 20,000                  |

Total cost of the post processing setup is TZS 140,210 (EUR 46.20). Excluded from this cost is the cost of the LPG container, costing TZS 20,000 for this 15.6 kg unit (EUR 6.59).

## A.5 Energy supply

Table A.5 gives a BOM overview of the parts and the costs of all the parts used in the electricity supply at the university.

Table A.5: University setup BOM: energy supply

| Nr.                    | Product                                            | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|----------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 51                     | Electrical cable<br>2X2.5 mm <sup>2</sup>          |    | 3,000                    | 5 m    | 15,000                  |
| 52                     | Timer EM-T180                                      |  | 45,000                   | 1      | 45,000                  |
| 53                     | Energy meter EM<br>0017-JC <sup>2</sup>            |  | 50,000                   | 2      | 100,000                 |
| 54                     | Circuit breaker MC<br>6K, 6 A, type C <sup>2</sup> |  | 4,500                    | 3      | 13,500                  |
| 55                     | Electrical box                                     |  | 24,500                   | 1      | 24,500                  |
| Continued on next page |                                                    |                                                                                      |                          |        |                         |

<sup>2</sup>Only one of each is needed for the absorption setup.



Table A.5 – continued from previous page

| Nr. | Product     | Picture                                                                            | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|-------------|------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 56  | Outlet plug |  | 3,500                    | 1      | 3,500                   |

Total cost of the energy supply is TZS 142,500 (EUR 46.96) for the absorption setup, and TZS 201,500 (EUR 66.40) for the water scrubbing setup.



## Appendix B

# Operating manual of the university setup

The next pages contain a manual, provided together with the setup. This manual consists of four chapters. The first chapter discusses the absorption system, explaining all the steps of operation, as well as maintenance. The second chapter is similar, but concerns the water scrubbing setup. The third chapter explains how to switch between the two setups. The final chapter includes a brief guidance for conducting biogas measurements on the system.



# Biogas Upgrading System – Step-by-Step Guide: Absorption system

**Important Note:** Make sure that the absorption column is connected at the top and bottom.

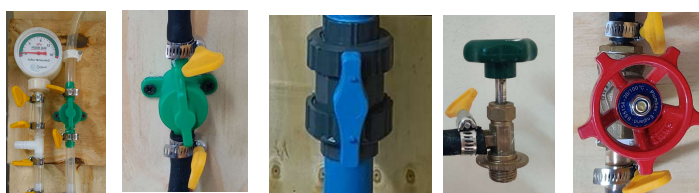
## 1. Connect the System

- Connect the input biogas line to the white connector.
- Connect the LPG tank to the LPG-valve.

## 2. Open the Valves

- Open the green input & output valves.
- Open the Column valve.
- Open the LPG-tank valve.
- **Close** the red measuring valve.

(all valves are shown in the open position)



## 3. Run the compression

- Turn on the system: switch the main (M) button to the on-position.
- Turn on the compressor: switch the compressor (C) button to the on-position.
- Monitor the pressure gauge.
- When the black gauge reaches 7 bar, turn off the compressor.



## 4. Disconnect the output

- Close the LPG valve.
- Disconnect the LPG-tank.



## 5. Maintenance

**Every 150 l of biogas production: replace the  $\text{Ca(OH)}_2$**

- Turn of the system.
- Close all valves (4 valves).
- Unscrew the bottom of the column.
- Clean the inside.
- Add 150g of  $\text{Ca(OH)}_2$  and fill with water.
- Screw the bottom back onto the valve.
- During the first run: check for leaks and fix if necessary.



1 scoop is 50g of  $\text{Ca(OH)}_2$

**Every 1000 l of biogas production:**

- Place the iron wool tank in open air to regenerate (10 hours), top up so the container stays full.
- Check the moisture traps and take out the water (screw back on tightly).
- Top up the water in the column by unscrewing the top connector and fill water until 70% full .



Filled iron wool tank



Empty moisture traps



Fill until 70%



# Biogas Upgrading System – Step-by-Step Guide: Water scrubbing setup

**Important Note:** Make sure that the water scrubbing column is connected at the top and bottom.

## 1. Connect the System

- Connect the input biogas line to the white connector.
- Connect the LPG tank to the LPG-valve.

## 2. Open the Valves

- Open the green input & output valves.
- Open the LPG-tank valve.
- Open the water valve.
- **Close** the red measuring valve.

(all valves are shown in the open position).



## 3. Run the water pump

- Fill the water jug upto the blue line.
- Turn on the system: switch the main (M) button to the on-position.
- Turn on the pump: switch the pump (P) button to the on-position.
- Close the water valve.
- Monitor the water level in the absorption tank.
- When the level reaches the red line, open the water valve slightly to let water out.
- Keep the water level around the red line by adjusting the water valve.



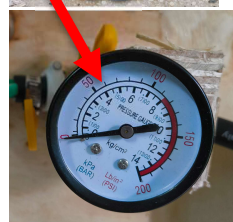
## 4. Run the compression

- Turn on the compressor: switch the compressor (C) button to the on-position.
- Monitor the pressure gauge.
- When the black gauge reaches 4 bar, turn off the compressor (C).



## 4. Disconnect the output

- Turn off the Pump (P).
- Close the LPG valve.
- Disconnect the LPG-tank.



## 5. Maintenance: every 1000 l of biogas production

- Place the iron wool tank in open air to regenerate (10 hours), top up so the container stays full.
- Check the moisture traps and take out the water (screw back on tightly).



Filled iron wool tank



Empty moisture traps

# Biogas Upgrading System – Step-by-Step Guide: Switch between setups

**Important Note:** Before beginning make sure the output pressure is 0, and the main (M) switch is turned off.

## 1. Close the Valves

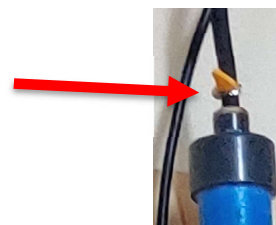
- Close the green input & output valves.
- Close the LPG-tank valve.
- Close the water valve.
- Close the red measuring valve.
- Close the column valve.

(all valves are shown in the open position).



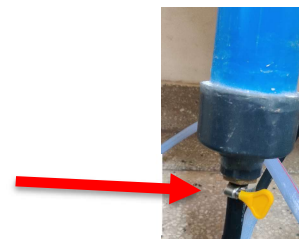
## 2. Remount the top

- Loosen the clamp at the top of the column.
- Take off the hose.
- Connect the hose to the other setup.
- Tighten the clamp tight onto the hose and connector.



## 3. Remount the bottom

- Loosen the clamp at the bottom of the column.
- Take off the hose.
- Connect the hose to the other setup.
- Tighten the clamp tight onto the hose and connector.
- When the system is turned on for the first time: check for leaks.



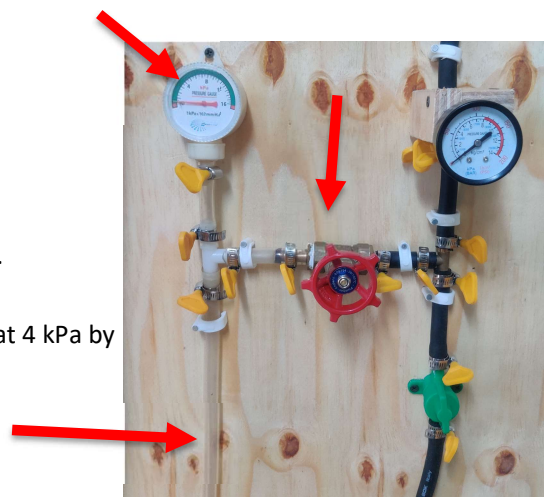
# Taking Measurements

## 1. Connect the biogas analyzer

- Connect the analyzer to the clear hose.

## 2. Take measurements

- Turn on the analyzer.
- Turn on the system as described in the step by step guide.
- Open the red valve.
- During pressure build up: keep the white pressure gauge at 4 kPa by closing the red valve slightly.



# Appendix C

## Explanatory videos of the university setup

The next page contains a QR code that links to a YouTube playlist containing 5 videos. The first provides an overview of the system's working principles; the second and third cover the operation of the absorption and water scrubbing setups, respectively; the fourth demonstrates the procedure for switching between the two setups; and the fifth explains how to use the system for conducting measurements.

**Scan for instruction videos:**



# Appendix D

## Overview of selected components of the Kimbiji setup

The initial investment cost of the Kimbiji setup using the absorption principle is TZS 1,386,470 (EUR 456.86). Excluded from this cost is the replacement cost of the rusted steel wool, and the  $Ca(OH)_2$ .

### D.1 Purification and compression setup

Table D.1 gives an overview of all the parts required for the purification and compression setup in Kimbiji.

Table D.1: Kimbiji setup BOM: purification and compression setup

| Nr.                    | Product       | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|---------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 1                      | Moisture trap |  | 5,000                    | 1      | 5,000                   |
| Continued on next page |               |                                                                                      |                          |        |                         |

Table D.1 – continued from previous page

| Nr.                    | Product                           | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 2                      | Compressor<br>ADW43               |    | 141,000                  | 1      | 141,000                 |
| 3                      | PVC water pipe 2<br>inch, grade C |   | 7,500                    | 1.8 m  | 13,800                  |
| 4                      | PVC-U, PN16 end-<br>cap 2 inch    |  | 5,000                    | 2      | 10,000                  |
| Continued on next page |                                   |                                                                                      |                          |        |                         |



Table D.1 – continued from previous page

| Nr.                    | Product                                                | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|--------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 5                      | PVC threaded<br>female socket<br>Ø26 mm to 3/4<br>inch |    | 2,000                    | 2      | 4,000                   |
| 6                      | PVC glue, PVC-U,<br>PN16                               |   | 15,000                   | 1      | 15,000                  |
| 7                      | Pressure gauge, 0-<br>14 bar                           |  | 20,000                   | 1      | 20,000                  |
| Continued on next page |                                                        |                                                                                      |                          |        |                         |



Table D.1 – continued from previous page

| Nr.                    | Product                           | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 8                      | Pressure gauge, 0-16 kPa          |    | 10,000                   | 1      | 10,000                  |
| 9                      | Brass nipple 15/16 inch to Ø10 mm |   | 11,800                   | 4      | 47,200                  |
| 10                     | Brass nipple 3/4 inch to Ø10 mm   |  | 5,000                    | 1      | 5,000                   |
| Continued on next page |                                   |                                                                                      |                          |        |                         |

Table D.1 – continued from previous page

| Nr.                    | Product                           | Picture                                                                             | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------------------|-------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 11                     | Brass nipple 3/4<br>inch to Ø8 mm |   | 5,000                    | 1      | 5,000                   |
| 12                     | Water filter, 125 psi             |  | 18,000                   | 2      | 36,000                  |
| Continued on next page |                                   |                                                                                     |                          |        |                         |

Table D.1 – continued from previous page

| Nr.                    | Product                      | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 13                     | T-connector, plastic, Ø10 mm |    | 2,000                    | 2      | 4,000                   |
| 14                     | Brass T-connector 8 mm       |    | 2,000                    | 1      | 2,000                   |
| 15                     | Biogas valve                 |  | 3,000                    | 3      | 9,000                   |
| 16                     | PVC-valve, 2 inch            |  | 45,000                   | 1      | 45,000                  |
| Continued on next page |                              |                                                                                      |                          |        |                         |

Table D.1 – continued from previous page

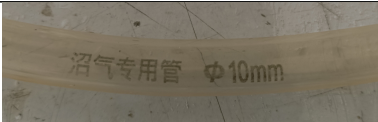
| Nr.                    | Product                | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 17                     | LPG valve              |    | 15,000                   | 1      | 15,000                  |
| 18                     | Clamps                 |   | 410                      | 28     | 11,480                  |
| 19                     | Biogas hose,<br>Ø10 mm |  | 1,000                    | 5 m    | 5,000                   |
| 20                     | Garden hose<br>Ø10 mm  |  | 1,200                    | 0.2 m  | 240                     |
| Continued on next page |                        |                                                                                      |                          |        |                         |



Table D.1 – continued from previous page

| Nr.                    | Product                                 | Picture | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|-----------------------------------------|---------|--------------------------|--------|-------------------------|
| 21                     | High pressure air<br>hose Ø10 mm        |         | 6,000                    | 1,5 m  | 9,000                   |
| 22                     | High pressure air<br>hose Ø8 mm         |         | 4,000                    | 5 m    | 20,000                  |
| 23                     | Empty LPG tank,<br>15.6 kg <sup>1</sup> |         | 20,000                   | 1      | 20,000                  |
| 24                     | Iron wool (15 g) <sup>2</sup>           |         | 500                      | 10     | 5,000                   |
| Continued on next page |                                         |         |                          |        |                         |

<sup>1</sup>This cost is not included in the cost calculation as this cost is an investment cost

<sup>2</sup>This cost is not included in the cost calculation as this cost is a maintenance cost.

Table D.1 – continued from previous page

| Nr. | Product                          | Picture                                                                            | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|----------------------------------|------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 25  | A bag of $Ca(OH)_2$ <sup>3</sup> |  | 1,400                    | 700 g  | 980                     |

The total cost of the setup is TZS 432,720 (EUR 142.59), added to this cost is the cost of the  $Ca(OH)_2$ , at a price of TZS 1,400/kg (EUR 0.46 /kg), and the price of an the LPG tank.

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<sup>3</sup>This cost is not included in the cost calculation as this cost is a mainenance cost.

## D.2 Energy supply

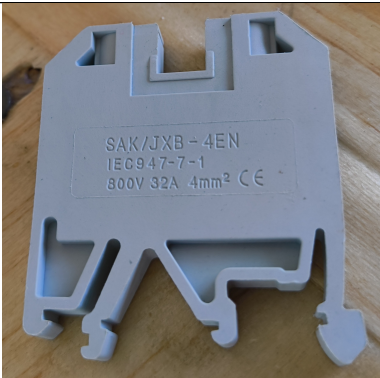
Table D.2 gives an overview of all the parts needed for the energy supply in Kimbiji.

Table D.2: Kimbiji setup BOM: energy supply

| Nr.                    | Product                                                              | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 26                     | Tronic flexible electrical Cable (2x4 mm <sup>2</sup> ) <sup>4</sup> |    | 4,500                    | 10 m   | 45,000                  |
| 27                     | Oceanic solar solar panel 200 W Monocrystalline                      |  | 250,000                  | 2      | 500,000                 |
| 28                     | Voltmax solar battery 50 Ah sealed                                   |  | 170,000                  | 1      | 170,000                 |
| Continued on next page |                                                                      |                                                                                      |                          |        |                         |

<sup>4</sup>Figure shown is representative and not the exact model used in the experiment.

Table D.2 – continued from previous page

| Nr. | Product                                                   | Picture                                                                              | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|-----------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 29  | Oceanic solar<br>PWM controller<br>60 A 12 V              |    | 130,000                  | 1      | 130,000                 |
| 30  | Oceanic solar In-<br>verter 12 V DC to<br>220 V AC, 600 W |    | 80,000                   | 1      | 80,000                  |
| 31  | Circuit breaker<br>MC 6K, 6 A, type<br>C                  |  | 4,500                    | 1      | 4,500                   |
| 32  | Circuit breaker<br>MC 6K, 20 A,<br>type C                 |  | 4,500                    | 1      | 4,500                   |
| 33  | DIN-rail terminal<br>block 4 mm <sup>2</sup>              |  | 1,000                    | 10     | 10,000                  |
| 34  | Fuse 63 A                                                 |  | 2,000                    | 1      | 2,000                   |

Continued on next page



Table D.2 – continued from previous page

| Nr. | Product     | Picture                                                                            | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|-------------|------------------------------------------------------------------------------------|--------------------------|--------|-------------------------|
| 35  | Outlet plug |  | 3,500                    | 1      | 3,500                   |
| 36  | DIN-rail    |  | 4,250                    | 1 m    | 4,250                   |

The total cost of the energy supply setup is TZS 953,750 (EUR 314.27).

## **Appendix E**

### **Operating Manual: Kimbiji setup**

# Biogas Upgrading System – Step-by-Step Guide

**Important Note:** This system can only operate when there is sunlight.

## 1. Connect the System

Connect the input biogas line to the white connector.

Connect the LPG tank to the LPG-valve.

## 2. Open the Valves

Open the input & output valves.

Open the Column valve.

Open the LPG-tank valve.

(all valves are shown in the open position)

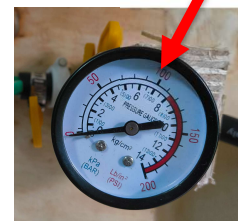


## 3. Run the compression

Turn on the compressor using the power switch.

Monitor the pressure gauge.

When the black gauge reaches 7 bar, turn off the compressor.



## 4. Disconnect the output

Close the output valve (on the LPG tank).

Disconnect the LPG-tank.

## 5. Maintenance

**Every week of biogas production (or 400l of biogas): replace the  $\text{Ca}(\text{OH})_2$**

Turn off the system.

Close all valves (4 valves).

Unscrew the bottom of the column.

Clean the inside.

Add 400g of  $\text{Ca}(\text{OH})_2$  and fill with water.

Screw the bottom back onto the valve.

During the first run: check for leaks and fix if necessary.



1 scoop is 50g of  $\text{Ca}(\text{OH})_2$

**Every 2 weeks of biogas production (or 1000l of biogas):**

Place the iron wool tank in open air to regenerate (10 hours), top up so the container stays full.

Check the moisture traps and take out the water (screw back on tightly).

Top up the water in the column by unscrewing the top connector and fill water until 70% full.



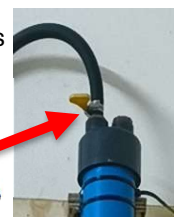
Filled iron wool tank



Empty moisture traps



Fill until 70%



# Appendix F

## proposed large-scale Kimbiji setup

This attachment illustrates a possible implementation for the purification, compression, and energy supplementary setup.

For each component, the corresponding part number from Attachment G is also given. The cables and hoses in this figure are:

- (A) - biogas hose (nr. 20),
- (B) - high pressure air hose (nr. 22),
- (C) - garden hose (nr. 21),
- (D) -  $2 \times 4 \text{ mm}^2$  electrical cable (nr. 25),
- (C) -  $2 \times 2.4 \text{ mm}^2$  electrical cable (nr. 26).

The setup is split into two parts. The first part is the compression and purification setup, which is given in Section F.1, Figure F.1. The energy supply is described in Section F.2, Figure F.2.

220 **F.1 Purification and compression**

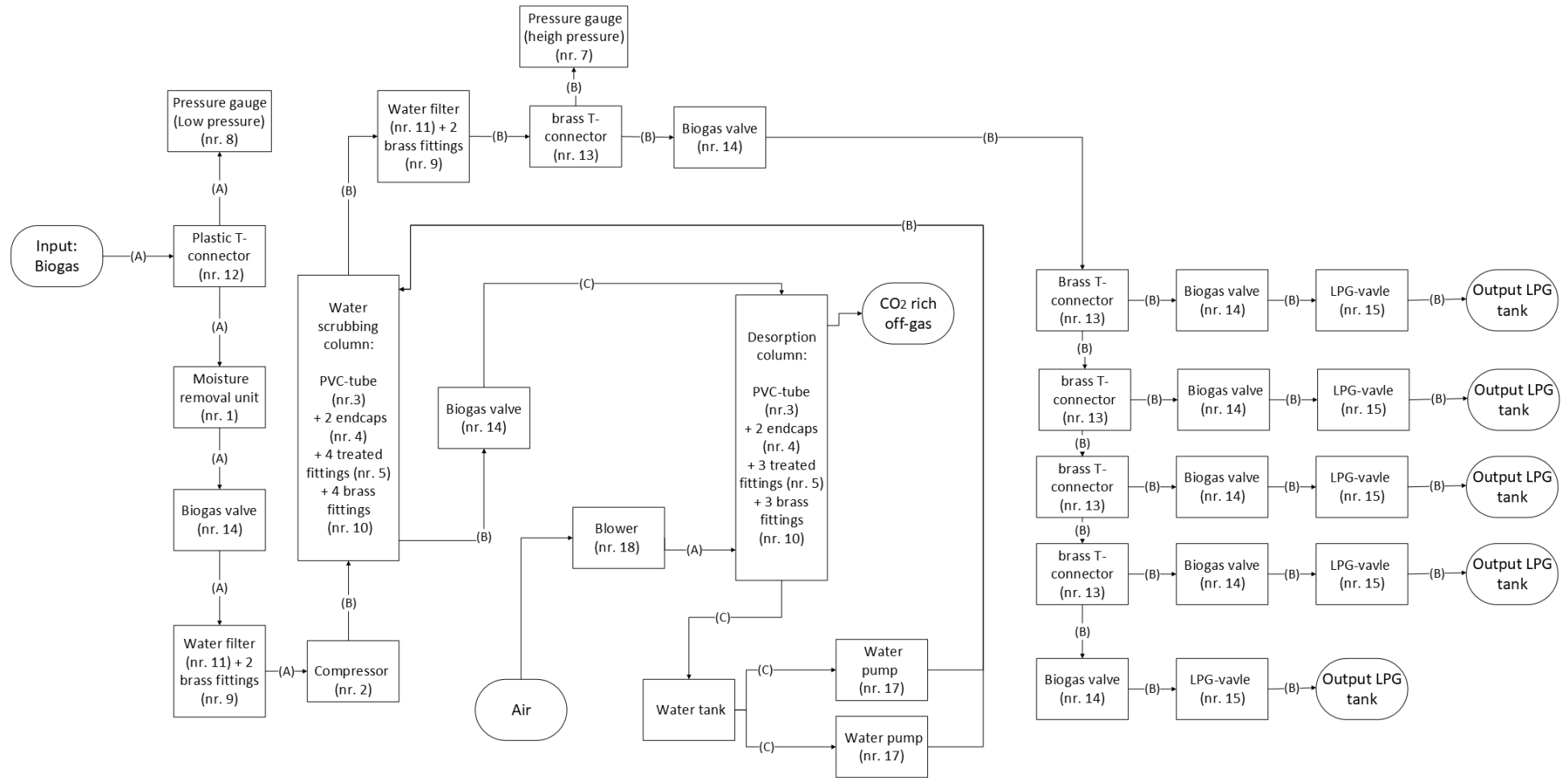


Figure F.1: Proposed large-scale Kimbiji purification and compression setup

## F.2 Energy supply

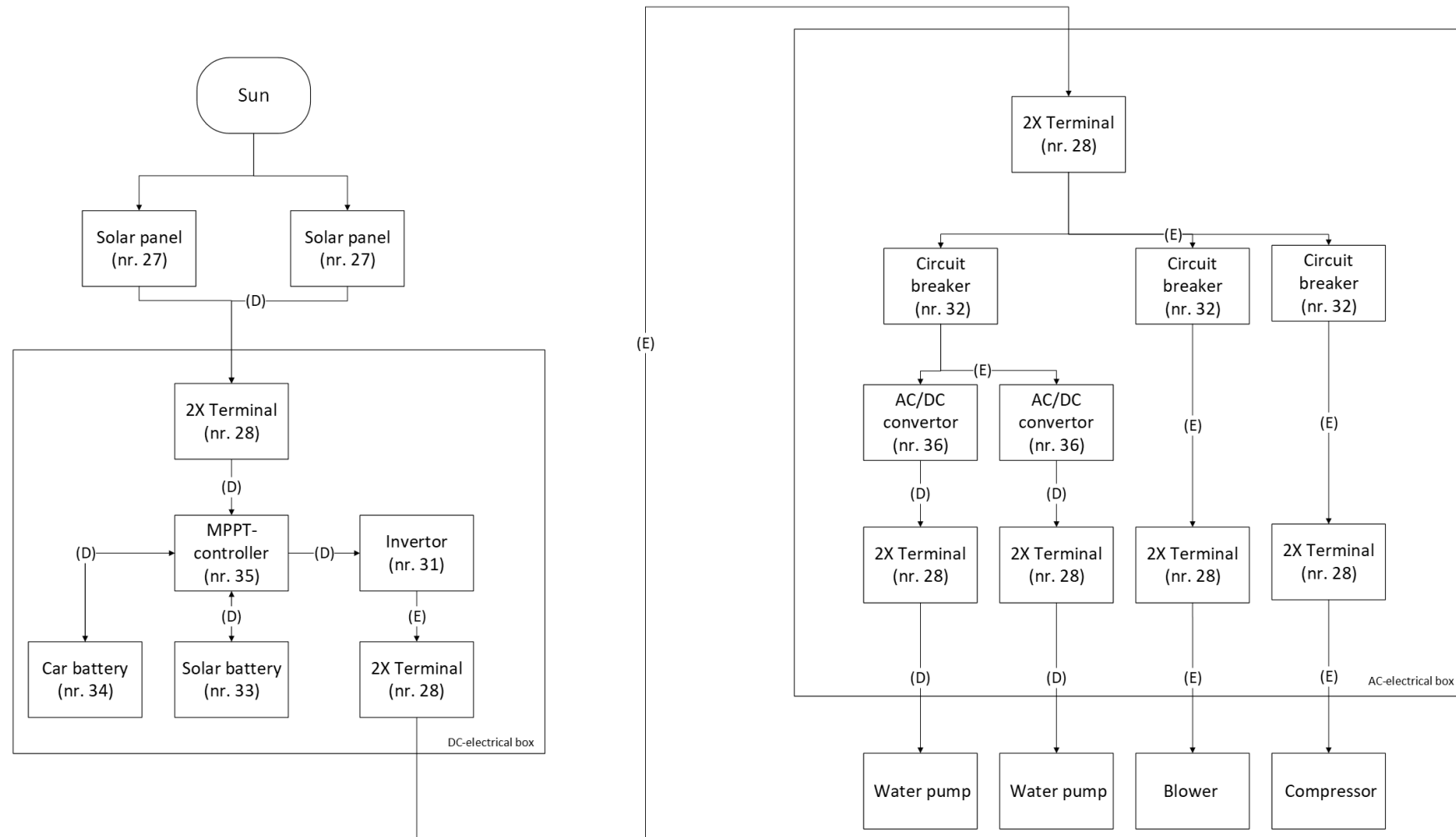


Figure F.2: Proposed large-scale Kimbiji energy supply



# Appendix G

## Overview of proposed components of the large-scale Kimbiji setup

The full investment cost for this setup is estimated to be TZS 3,007,230 (EUR 990.92).

### G.1 Purification and compression setup

Table G.1 illustrates the proposed components of the purification and compression setup for the full scale Kimbiji setup.

Table G.1: Proposed large-scale Kimbiji setup BOM

| Nr.                    | Product                                          | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|------------------------|--------------------------------------------------|--------------------------|--------|-------------------------|
| 1                      | Moisture trap                                    | 5,000                    | 1      | 5,000                   |
| 2                      | Compressor ADW77                                 | 177,000                  | 1      | 177,000                 |
| 3                      | PVC water pipe 2 inch, grade C                   | 7,500                    | 2.0 m  | 15,000                  |
| 4                      | PVC-U, PN16 endcap 2 inch                        | 5,000                    | 4      | 20,000                  |
| 5                      | PVC threaded female socket<br>Ø26 mm to 3/4 inch | 2,000                    | 7      | 14,000                  |
| 6                      | PVC glue, PVC-U, PN16                            | 15,000                   | 1      | 15,000                  |
| 7                      | Pressure gauge, 0-14 bar                         | 20,000                   | 1      | 20,000                  |
| 8                      | Pressure gauge, 0-16 kPa                         | 10,000                   | 1      | 10,000                  |
| 9                      | Brass nipple 15/16 inch to<br>Ø10 mm             | 11,800                   | 4      | 47,200                  |
| 10                     | Brass nipple 3/4 inch to Ø8 mm                   | 5,000                    | 7      | 35,000                  |
| 11                     | Water filter, 125 psi                            | 18,000                   | 2      | 36,000                  |
| 12                     | T-connector, plastic, Ø10 mm                     | 2,000                    | 1      | 2,000                   |
| 13                     | Brass T-connector 8 mm                           | 2,000                    | 5      | 10,000                  |
| 14                     | Biogas valve                                     | 3,000                    | 8      | 24,000                  |
| 15                     | LPG valve                                        | 15,000                   | 5      | 75,000                  |
| Continued on next page |                                                  |                          |        |                         |



Table G.1 – continued from previous page

| Nr. | Product                                    | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|--------------------------------------------|--------------------------|--------|-------------------------|
| 16  | Clamps                                     | 410                      | 58     | 23,780                  |
| 17  | Water booster pump<br>GMB782432            | 190,000                  | 2      | 380,000                 |
| 18  | Biogas booster pump                        | 100,000                  | 1      | 100,000                 |
| 19  | Used water jug                             | /                        | 3 m    | /                       |
| 20  | Biogas hose, Ø10 mm                        | 1,000                    | 3 m    | 3,000                   |
| 21  | Garden hose Ø10 mm                         | 1,200                    | 5 m    | 6,000                   |
| 22  | High pressure air hose Ø8 mm               | 4,000                    | 10 m   | 40,000                  |
| 23  | Empty LPG tank, 15.6 kg <sup>1</sup>       | 20,000                   | 5      | 100,000                 |
| 24  | Granulated Iron oxide (750 g) <sup>1</sup> | 3,500                    | 1      | 35,000                  |

The price for the purification and compression setup for this scale is TZS 1,057,980 (EUR 348.62). The inventory holding cost and replacement cost for the  $H_2S$  absorbent are not counted here.

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<sup>1</sup>This price is not counted as it is not part of the investment cost, but part of the inventory holding cost

## G.2 Energy supply

Table G.2: Proposed large-scale Kimbiji setup BOM: Energy supply

| Nr. | Product                                           | Price/<br>piece<br>[TZS] | Pieces | Total<br>price<br>[TZS] |
|-----|---------------------------------------------------|--------------------------|--------|-------------------------|
| 25  | Tronic electrical cable 2X4 $mm^2$                | 4,500                    | 10 m   | 45,000                  |
| 26  | Tronic electrical cable 2X2.5 $mm^2$              | 3,000                    | 10 m   | 30,000                  |
| 27  | Oceanic solar solar panel 500 W Monocrystalline   | 550,000                  | 2      | 1,100,000               |
| 28  | DIN-rail terminal block 4 $mm^2$                  | 1,000                    | 14     | 14,000                  |
| 29  | Outlet plug                                       | 3,500                    | 1      | 3,500                   |
| 30  | DIN-rail                                          | 4,250                    | 1 m    | 4,250                   |
| 31  | Oceanic solar inverter 12 V DC to 220 V AC, 600 W | 80,000                   | 1      | 80,000                  |
| 32  | Circuit breaker MC 6K, 6 A, type C                | 4,500                    | 4      | 18,000                  |
| 33  | Voltmax solar battery 50 Ah sealed                | 170,000                  | 1      | 170,000                 |
| 34  | Car battery 45 Ah flooded                         | 120,000                  | 1      | 120,000                 |
| 35  | MPPT controller 60 A 12 V                         | 300,000                  | 1      | 300,000                 |
| 36  | DC power supply 240 V to 24 V, 3 A                | 3,000                    | 2      | 6,000                   |

The total cost of the energy supply setup is TZS 1,890,750 (EUR 623.03).



# Appendix H

## NPV overview tables

This attachment outlines the NPV overview tables. All prices are expressed per TZS 1,000. For each year, the present value (PV) is calculated.

# H.1 Small-scale setup

Table H.1: NPV analysis of the small-scale system, expressed in TZS 1,000

| Category                      | Year 0 | Year 1                | Year 2                | Year 3                | Year 4                | Year 5                | Year 6                | Year 7                | Year 8                | Year 9                                  | Year 10               |
|-------------------------------|--------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------------------------|-----------------------|
| <b>CAPEX</b>                  |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Purification setup            | −433   | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                                       | −                     |
| Energy supply                 | −477   | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                                       | −                     |
| Digester cost                 | −1,313 | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                                       | −                     |
| <b>OPEX</b>                   |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Absorbent                     | −      | −31                   | −31                   | −31                   | −31                   | −31                   | −31                   | −31                   | −31                   | −31                                     | −31                   |
| Battery replacement           | −      | −57                   | −57                   | −57                   | −57                   | −57                   | −57                   | −57                   | −57                   | −57                                     | −57                   |
| <b>Inventory holding cost</b> |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| LPG tanks & stock             | −124   | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                     | −                                       | 124                   |
| <b>Revenues</b>               |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Biogas sales                  | −      | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$        | $0.25 \cdot P$                          | $0.25 \cdot P$        |
| Net cash flow                 | −2347  | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$   | $0.25 \cdot P - 88$                     | $0.25 \cdot P + 36$   |
| Discount factor (%)           | 100%   | 95%                   | 90%                   | 86%                   | 81%                   | 77%                   | 74%                   | 70%                   | 66%                   | 63%                                     | 60%                   |
| Present value                 | −2347  | $0.23 \cdot P - 84$   | $0.22 \cdot P - 79$   | $0.21 \cdot P - 75$   | $0.20 \cdot P - 72$   | $0.19 \cdot P - 68$   | $0.18 \cdot P - 65$   | $0.17 \cdot P - 61$   | $0.16 \cdot P - 58$   | $0.15 \cdot P - 55$                     | $0.15 \cdot P + 22$   |
| Cumulative PV                 | −2347  | $0.23 \cdot P - 2430$ | $0.45 \cdot P - 2510$ | $0.67 \cdot P - 2585$ | $0.87 \cdot P - 2657$ | $1.06 \cdot P - 2725$ | $1.24 \cdot P - 2789$ | $1.41 \cdot P - 2851$ | $1.57 \cdot P - 2909$ | $1.72 \cdot P - 2965$                   | $1.87 \cdot P - 2943$ |
| NPV                           |        |                       |                       |                       |                       |                       |                       |                       |                       | <b><math>1.87 \cdot P - 2943</math></b> |                       |

## H.2 Large-scale setup

Table H.2: NPV analysis of the large-scale system, expressed in TZS 1,000

| Category                      | Year 0  | Year 1                | Year 2                | Year 3                | Year 4                | Year 5                | Year 6                | Year 7                | Year 8                 | Year 9                                   | Year 10                |
|-------------------------------|---------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------|------------------------------------------|------------------------|
| <b>CAPEX</b>                  |         |                       |                       |                       |                       |                       |                       |                       |                        |                                          |                        |
| Purification setup            | -1,058  | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                      | -                                        | -                      |
| Energy supply                 | -1,891  | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                      | -                                        | -                      |
| Digester cost                 | -23,232 | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                      | -                                        | -                      |
| <b>OPEX</b>                   |         |                       |                       |                       |                       |                       |                       |                       |                        |                                          |                        |
| $H_2S$ Absorbent              | -       | -8                    | -8                    | -8                    | -8                    | -8                    | -8                    | -8                    | -8                     | -8                                       | -8                     |
| Battery replacement           | -       | -97                   | -97                   | -97                   | -97                   | -97                   | -97                   | -97                   | -97                    | -97                                      | -97                    |
| <b>Inventory holding cost</b> |         |                       |                       |                       |                       |                       |                       |                       |                        |                                          |                        |
| LPG tanks & stock             | -5,814  | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                      | -                                        | 5,814                  |
| <b>Revenues</b>               |         |                       |                       |                       |                       |                       |                       |                       |                        |                                          |                        |
| Biogas sales                  | -       | $15.95 \cdot P$       | $15.95 \cdot P$       | $15.95 \cdot P$       | $15.95 \cdot P$       | $15.95 \cdot P$       | $15.95 \cdot P$       | $15.95 \cdot P$       | $15.95 \cdot P$        | $15.95 \cdot P$                          | $15.95 \cdot P$        |
| <b>Net cash flow</b>          | -31,992 | $16 \cdot P - 105$    | $16 \cdot P - 105$    | $16 \cdot P - 105$    | $16 \cdot P - 105$    | $16 \cdot P - 105$    | $16 \cdot P - 105$    | $16 \cdot P - 105$    | $16 \cdot P - 105$     | $16 \cdot P - 105$                       | $16 \cdot P + 5,814$   |
| <b>Discount factor (%)</b>    | 100%    | 95%                   | 90%                   | 86%                   | 81%                   | 77%                   | 74%                   | 70%                   | 66%                    | 63%                                      | 60%                    |
| <b>Present value</b>          | -31,992 | $15 \cdot P - 99$     | $14 \cdot P - 94$     | $14 \cdot P - 90$     | $13 \cdot P - 85$     | $12 \cdot P - 81$     | $12 \cdot P - 77$     | $11 \cdot P - 73$     | $11 \cdot P - 69$      | $10 \cdot P - 66$                        | $10 \cdot P + 3,416$   |
| <b>Cumulative PV</b>          | -31,992 | $15 \cdot P - 32,091$ | $30 \cdot P - 32,185$ | $43 \cdot P - 32,275$ | $56 \cdot P - 32,360$ | $69 \cdot P - 32,441$ | $80 \cdot P - 32,518$ | $92 \cdot P - 32,591$ | $102 \cdot P - 32,660$ | $112 \cdot P - 32,726$                   | $122 \cdot P - 29,309$ |
| <b>NPV</b>                    |         |                       |                       |                       |                       |                       |                       |                       |                        | <b><math>122 \cdot P - 29,309</math></b> |                        |

## H.3 Alternative fuel sources: Solar and hybrid solar-biogas power

Table H.3: NPV analysis of solar powered cooking, expressed in TZS 1,000

| Category             | Year 0 | Year 1                | Year 2                | Year 3                | Year 4                | Year 5                | Year 6                | Year 7                | Year 8                | Year 9                                  | Year 10               |
|----------------------|--------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------------------------|-----------------------|
| <b>CAPEX</b>         |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Energy supply        | -954   | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                                       | -                     |
| Cooking stove        | -89    | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                                       | -                     |
| <b>OPEX</b>          |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Battery replacement  | -      | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                                     | -57                   |
| <b>Revenues</b>      |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Solar revenue        | -      | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$                          | $0.22 \cdot P$        |
| <b>Net cash flow</b> | -1043  | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$                     | $0.22 \cdot P - 57$   |
| <b>PV factor (%)</b> | 100%   | 95%                   | 90%                   | 86%                   | 81%                   | 77%                   | 74%                   | 70%                   | 66%                   | 63%                                     | 60%                   |
| <b>Present value</b> | -1043  | $0.22 \cdot P - 54$   | $0.21 \cdot P - 51$   | $0.20 \cdot P - 49$   | $0.19 \cdot P - 46$   | $0.18 \cdot P - 44$   | $0.17 \cdot P - 42$   | $0.16 \cdot P - 40$   | $0.15 \cdot P - 38$   | $0.15 \cdot P - 36$                     | $0.14 \cdot P - 34$   |
| <b>Cumulative PV</b> | -1043  | $0.21 \cdot P - 1097$ | $0.41 \cdot P - 1148$ | $0.59 \cdot P - 1196$ | $0.77 \cdot P - 1242$ | $0.94 \cdot P - 1286$ | $1.10 \cdot P - 1328$ | $1.26 \cdot P - 1368$ | $1.40 \cdot P - 1405$ | $1.54 \cdot P - 1441$                   | $1.67 \cdot P - 1475$ |
| Category             | -      | Year 11               | Year 12               | Year 13               | Year 14               | Year 15               | Year 16               | Year 17               | Year 18               | Year 19                                 | Year 20               |
| <b>CAPEX</b>         |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Energy supply        | -      | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                                       | -                     |
| Cooking stove        | -      | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                                       | -                     |
| <b>OPEX</b>          |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Battery replacement  | -      | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                                     | -57                   |
| <b>Revenues</b>      |        |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Solar revenue        | -      | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$                          | $0.22 \cdot P$        |
| <b>Net cash flow</b> | -      | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$                     | $0.22 \cdot P - 57$   |
| <b>PV factor (%)</b> | -      | 57%                   | 54%                   | 51%                   | 49%                   | 46%                   | 44%                   | 42%                   | 40%                   | 38%                                     | 36%                   |
| <b>Present value</b> | -      | $0.13 \cdot P - 32$   | $0.12 \cdot P - 31$   | $0.12 \cdot P - 29$   | $0.11 \cdot P - 28$   | $0.11 \cdot P - 26$   | $0.10 \cdot P - 25$   | $0.10 \cdot P - 24$   | $0.09 \cdot P - 23$   | $0.09 \cdot P - 21$                     | $0.08 \cdot P - 20$   |
| <b>Cumulative PV</b> | -      | $1.79 \cdot P - 1507$ | $1.91 \cdot P - 1538$ | $2.02 \cdot P - 1567$ | $2.13 \cdot P - 1594$ | $2.23 \cdot P - 1621$ | $2.33 \cdot P - 1646$ | $2.42 \cdot P - 1669$ | $2.51 \cdot P - 1692$ | $2.59 \cdot P - 1713$                   | $2.67 \cdot P - 1733$ |
| <b>NPV</b>           |        |                       |                       |                       |                       |                       |                       |                       |                       | <b><math>2.67 \cdot P - 1733</math></b> |                       |

Table H.4: NPV analysis of the hybrid solar-biogas installation, expressed in TZS 1,000

| Category                      | Year 0                | Year 1                | Year 2                | Year 3                | Year 4                | Year 5                | Year 6                | Year 7                | Year 8                | Year 9                                  | Year 10               |
|-------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------------------------|-----------------------|
| <b>CAPEX</b>                  |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Purification setup            | -433                  | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| Energy supply                 | -954                  | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| Digester cost                 | -1,313                | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| <b>OPEX</b>                   |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Absorbent cost                | –                     | -31                   | -31                   | -31                   | -31                   | -31                   | -31                   | -31                   | -31                   | -31                                     | -31                   |
| Battery replacement           | –                     | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                   | -57                                     | -57                   |
| <b>Inventory holding cost</b> |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| LPG tanks & stock             | -124                  | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | 124                   |
| <b>Revenues</b>               |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Solar revenue                 | -                     | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$                          | $0.22 \cdot P$        |
| Biogas revenue                | -                     | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$        | $0.24 \cdot P$                          | $0.24 \cdot P$        |
| <b>Net cash flow</b>          | $0.46 \cdot P - 2823$ | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$   | $0.46 \cdot P - 88$                     | $0.46 \cdot P + 36$   |
| <b>PV factor (%)</b>          | 100%                  | 95%                   | 90%                   | 86%                   | 81%                   | 77%                   | 74%                   | 70%                   | 66%                   | 63%                                     | 60%                   |
| <b>Present value</b>          | -2823                 | $0.44 \cdot P - 84$   | $0.42 \cdot P - 79$   | $0.40 \cdot P - 75$   | $0.38 \cdot P - 72$   | $0.36 \cdot P - 68$   | $0.34 \cdot P - 65$   | $0.32 \cdot P - 61$   | $0.31 \cdot P - 58$   | $0.29 \cdot P - 55$                     | $0.28 \cdot P + 22$   |
| <b>Cumulative PV</b>          | -2823                 | $0.44 \cdot P - 2907$ | $0.86 \cdot P - 2986$ | $1.26 \cdot P - 3062$ | $1.64 \cdot P - 3134$ | $2.00 \cdot P - 3202$ | $2.34 \cdot P - 3266$ | $2.66 \cdot P - 3328$ | $2.97 \cdot P - 3386$ | $3.26 \cdot P - 3442$                   | $3.54 \cdot P - 3420$ |
| Category                      | -                     | Year 11               | Year 12               | Year 13               | Year 14               | Year 15               | Year 16               | Year 17               | Year 18               | Year 19                                 | Year 20               |
| <b>CAPEX</b>                  |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Purification setup            | -                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| Energy supply                 | -                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| Digester cost                 | -                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| <b>OPEX</b>                   |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Absorbent cost                | –                     | -31                   | -31                   | -31                   | -31                   | -31                   | -31                   | -31                   | -31                   | -31                                     | -31                   |
| Battery replacement           | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | –                     |
| <b>Inventory holding cost</b> |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| LPG tanks & stock             | -                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                     | –                                       | -                     |
| <b>Revenues</b>               |                       |                       |                       |                       |                       |                       |                       |                       |                       |                                         |                       |
| Solar revenue                 | -                     | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$        | $0.22 \cdot P$                          | $0.22 \cdot P$        |
| Biogas revenue                | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                     | -                                       | -                     |
| <b>Net cash flow</b>          | -                     | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$   | $0.22 \cdot P - 57$                     | $0.22 \cdot P - 57$   |
| <b>PV factor (%)</b>          | -                     | 57%                   | 54%                   | 51%                   | 49%                   | 46%                   | 44%                   | 42%                   | 40%                   | 38%                                     | 36%                   |
| <b>Present value</b>          | -                     | $0.12 \cdot P - 32$   | $0.12 \cdot P - 31$   | $0.11 \cdot P - 29$   | $0.11 \cdot P - 28$   | $0.10 \cdot P - 26$   | $0.10 \cdot P - 25$   | $0.09 \cdot P - 24$   | $0.09 \cdot P - 23$   | $0.08 \cdot P - 21$                     | $0.08 \cdot P - 20$   |
| <b>Cumulative PV</b>          | -                     | $3.67 \cdot P - 3452$ | $3.78 \cdot P - 3483$ | $3.90 \cdot P - 3512$ | $4.00 \cdot P - 3540$ | $4.11 \cdot P - 3566$ | $4.20 \cdot P - 3591$ | $4.29 \cdot P - 3614$ | $4.38 \cdot P - 3637$ | $4.46 \cdot P - 3658$                   | $4.54 \cdot P - 3679$ |
| <b>NPV</b>                    |                       |                       |                       |                       |                       |                       |                       |                       |                       | <b><math>4.54 \cdot P - 3679</math></b> |                       |