ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING
GRADUATE PROGRAM IN THERMAL ENGINEERING

UPGRADING BIOGAS FOR SMALL – SCALE ELECTRICITY GENERATION FROM FOOD WASTE, A CASE STUDY OF SIDIST KILO UNIVERSITY

A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the Degree of Masters of Science in Mechanical and Industrial Engineering

By: Tamrat Moges

Advisor: Dr.-Ing. Wondwossen Bogale

Addis Ababa, Ethiopia
October 2018

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES
ENERGY CENTER

UPGRADING BIOGAS FOR SMALL – SCALE ELECTRICITY GENERATION FROM FOOD WASTE,

(A CASE STUDY OF SIDIST KILO UNIVERSITY)

Submitted by:

Tamrat Moges	____________________	____________________
Name	Date	Signature

Approved by Board of Examiners

Dr. Ing. Wondossen Bogale		
Advisor	Date	Signature
Dr. Kamil Dino		
Internal Examiner	Date	Signature
Dr. Ing. Demiss Alemu		
External Examiner	Date	Signature
Dr. Yilma Taddese		
Chairman of SMIE	Date	Signature
Dr. Ermias Tesfaye		
Director of Post Graduate	Date	Signature

ACKNOWLEDGMENTS

Above all, I would like to express my deep sense of gratitude to the Almighty God for his unconditional love, support and everything he has done to me.

Then I would like to express my sincere gratitude and heartfelt appreciation to my advisor Dr.-Ing. Wondwossen Bogale, Director of University Industry Linkage, and Technology Transfer of Addis Ababa University for his, guidance and persistent encouragement during the period of my work.

In addition, my gratitude also goes to the Adama science and Technology University for sponsoring me to attend my Graduate School Program.

Finally, I would like to pass my heartfelt gratitude to my family and friends for their support and encouragement for the successful accomplishment of this thesis paper.

ABSTRACT

Now a day's biogas from food waste is an alternative and a viable energy sources for domestic energy consumption. Hence, this research is concerned with biogas upgrading for electricity generation. To do this 115kg of food waste collected from student cafeterias in Addis Ababa Sidist Kilo University used to produce 10.35m^3 biogas per day using 10m^{3}digester (fiberglass roto tanker). According to the data collected from the kitchen, 41,975kg food waste is available to produce 3,777.75m^3 Biogas per year.

Due to the degree of purification and economical aspects, chemical absorption process specifically using $Ca(OH)_2$ solution has been selected to remove CO_2 from biogas. In addition, biogas cleaning is also done using silica gel and Activated carbon in order to remove H_2O vapor and H_2S respectively. After purification, the result found from the experiment will validate by crosschecking it with Matlab result and result found from literature.

Compressing biomethane minimize storage space, concentrates its energy content, and increases pressure to the required level through overcoming resistance to gas flow. From the result, the compressor designed to compress 6.73m^3 biomethane in to 2.5m^3 for this system the pressure increased from 1.106bar to 4bar.

As the research shows based on the investment cost, availability, and simplicity during modification, gasoline generator became suitable to be used and generate 54.9kW electric power per day for 9 hour using 6.1kW rated power generator.

The research indicates, economical as well as environmental benefits of biogas upgrading technology in which the campus gained through producing 2,455.54m^3 biomethane per year. This is equivalent with 17barrel of gasoline fuel. Moreover, it implies the potential of generating 20.04MW of electricity per year from the campus food waste.

From economical perspective, it was possible to see that the Biogas Upgrading for electricity is financially as well as economically feasible as the NPV is positive and benefit cost ratio is greater than one. As financial analysis indicates, biomethane production will save 77,945Birr annually that can be expended for Gasoline fuel.

Key words:- Upgrading, food waste, biomethane, gasoline and modification.

DECLARATION

I declare that this thesis entitled "**Upgrading Biogas for Small–Scale Electricity Generation from Food Waste, A Case Study Of Sidist Kilo University**" is my original work done under the supervisor of Dr.-Ing. Wondwossen Bogale at Addis Ababa Institute of Technology during the year 2018 as part of Master of Science degree in thermal Engineering and has not been presented for a degree in any other university and that all the sources of materials used for the thesis have been correctly acknowledged.

Name	Signature	date
Tamrat Moges	______________	________________
Name		

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr.-Ing. Wondwossen Bogale	__________________	______________
Thesis Advisor	Signature	Date

Table of Contents

LIST OF FIGURE

LIST OF TABLE

ACRONYMS

AD	Anaerobic Digestion
AF	Air-fuel ratio
BCR	Benefit-Cost Ratio
C/N	Carbon/Nitrogen ratio
CHP	Combined Heat and Power
EEPCO	Ethiopia Electric Light and Power Authority
GAC	Granular Activated Carbon
GHG	Greenhouse Gases
HDPE	High Density Polyethylene
HRT	Hydraulic Retention Time
IRR	Internal Rate of Return
kPa	kilo Pascal
kWh	kilo Watt hour
MEA	Mono-Ethanolamine
NPV	Net Present Value
PAC	Powdered Activated Charcoal
pH	Meter
PPR	Polypropylene Polymer Random
PVC	Poly Vinyl Chloride
RH	Relative Humidity
SFW	Solid Food Waste
SPP	Simple Payback Period
TS	Total Solid
Vol.	Volume
VS	Volatile Solid

CHAPTER ONE

1.1. Introduction

Energy is one of the major inputs for the economic growth of any country. It is a well-known fact that the development of a given nation has direct connection with the amount of energy consumption. The high standards of living in the developed countries are manifestation to high-energy consumption levels.

Because of the exhaustible nature of primary energy sources or nonrenewable energy sources; such as (coal, oil and natural gas) and their continually diminishing supply with increasing consumption causes the rising on prices [1]. Not only this, the dramatically increment of global warming implies that the increased effect of greenhouse gases (carbon dioxide) emission[2]. As the studies indicate combustion of fossil fuel responsible for more than 62% of the global warming [3]. These and other factors are the driving forces, which led to searches for renewable energy sources and are consequence for development of renewable energy production technologies.

Biogas produced from organic wastes through anaerobic digestion (AD) brings an excellent solution to the above problems[4]. Specially, kitchen waste is the best alternative for biogas production in a community as well as in national level. Biochemical process of AD consists of a large group of complex and differently acting microbe species, which is known by the methane-producing bacteria. The whole biogas-process consists of four major steps: hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis (methane formation).

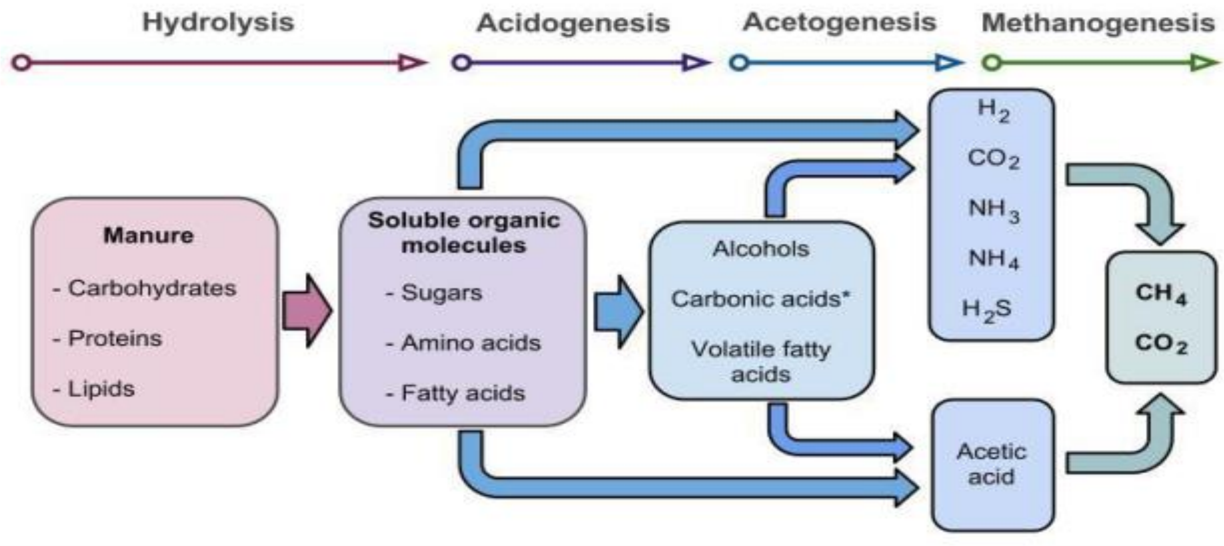


Figure 1.1: Hydrolysis, acidogenesis, acetogenesis, and methanogenesis stage of anaerobic digestion [5].

Typically biogas consists of 55–70% methane (CH_4), 30–45% carbon dioxide (CO_2), 1–4% water (H_2O), 1-2 % hydrogen sulfide (H_2S) and other minor trace gases[5].

Apart from methane and carbon dioxide, biogas also contains water vapor, hydrogen sulphide, and other unwanted trace components. Hence, biogas is generally subjected to a pre-treatment stage (i.e. biogas cleaning stage) before upgrading process. Basically this is done in-order to remove water vapor and hydrogen sulfide from the raw gas using silica gel and activated carbon, respectively. Moreover, biogas cleaning has meaning full role towards preventing corrosion inside downstream materials.

In addition, the problem exists again is a low-grade fuel with 20MJ/m^3 calorific value due to existence of CO_2 gas will deliver less power output. Hence, the presence of CO_2 in biogas led to search different upgrading technologies. This helps to purify it in to natural gas standard by increasing its calorific value through enhancing its Methane content. After the purification, biogas can be referred as biomethane.

Now days, different upgrading methods are discovered towards removing CO_2 from biogas, based on physical and chemical properties of CO_2 gas. Water scrubber, pressure swing adsorption, membrane, cryogenic separation and chemical scrubber are exists among the upgrading methods [6].

The main objective of this paper is to upgrade biogas by using a chemical absorption process specifically using NaOH solution. This aimed at producing methane enrich gas and generate environmentally friendly fuel utilized for electric power generation.

There are different methods to convert biomethane fuel into electric power. It possible to generate electricity by using:

- ✓ 100% biogas generator,
- ✓ Dual fuel generator it can be either gasoline or diesel,
- ✓ Genset (engine-generator set),
- ✓ Combined heat and power and
- ✓ Steam power plant

Detail discussion is made on selection of power generation system and power generation process in chapter 6.

After upgrading biogas can provides the following economical as well as environmental advantages:

Economic advantages of biomethane:

- ❖ It can be used for electricity generation at local scale as well as national level.
- ❖ It is also used as a substitution of natural gas with low cost.
- ❖ It is possible to use it as a vehicle fuel either by blending with diesel fuel or by using it alone.
- ❖ Reduces import expense from fossil fuel such as gasoline and diesel fuel.
- ❖ For electrification of rural areas as well as it serves as back up fuel for electric generator in urban area with low operating costs.
- ❖ Reduce maintenance cost by minimizing damage from highly corrosive acid gas H_2S and moisture (H_2O).
- ❖ It prevents dependency on degradable and pollutant fossil fuel.
- ❖ Provide new job opportunities.

Environmental advantages biomethane:

- ➢ It mitigates GHG emission such as emission of CO_2 and CH_4.
- ➢ It is significant for waste management in both urban and rural area and helpful to create healthy and attractive environment.

- It is possible to use sludge as an organic fertilizer.
- Reduce poisonous H_2S gas to prevent acidic rain.

Finally, in Ethiopia, most researches conducted related to biogas energy were focused on biogas production for heat generation and direct lighting, but this thesis prepared to introduce the significance of upgrading biogas to generate electricity in better ways and enhance technology transfer.

1.2. Background

There are variations among authors to identify the exact time when biogas was introduced into Ethiopia by Ambo Agricultural College around 1957 to supply the energy for welding agricultural tools. The type of model for this first installed biogas digester was a batch type digester [7].

According to National Biogas Program in Ethiopia biogas technology was introduced as early as 1979. In the last two and a half decades, around 1000 biogas plants were constructed in various parts of the country. Presently, approximately 40 % of these plants are not operational due to a lack of effective management and follow-up, technical problems, evacuation of ownership and water problems [7].

Due to corrosion, biogas needs to be cleaned before upgrading and after cleaning and upgrading it is suitable to uses it for internal combustion engine. Cleaning biogas includes moisture, Hydrogen Sulphide (H_2S) and dust removal [8].

Absorption is a process of transferring a component from its gas phase into a liquid provided that the gas is soluble in that liquid. In the case of CO_2, the solubility of the gas is dependent on the solvent physical and chemical properties[9].

An early use of amine scrubbing for CO_2 removal was reported in 1930. The amines recommended for the CO_2 scrubbing were primary, secondary, and tertiary and contain a carboxyl group. One early study claimed that the effectiveness of mono-ethanolamine and di-amino-isopropanol is twice that of tri-ethanolamine[9].

Caustic solvents (sodium hydroxide, potassium hydroxide, and calcium hydroxide) are the second most abundant solvents which can chemically absorb CO_2 from a mixture of gases after amine solutions. These alkaline solutions have been studied by several researchers for their absorption capacity to CO_2, for more than 50 years [9]. Many of the early-published work on CO_2 absorption by caustic solutions focused on the use of sodium hydroxide[10].

A suspension of lime ($Ca(OH)_2$ solution) for the absorption of CO_2 has been performed. In their study, the researchers used a bubble column with agitated contactors. In general, less attention was given to CO_2 absorption using $Ca(OH)_2$ due to the low solubility of the first in water which makes it not suitable to be used at higher CO_2 concentrations[11].

Internal combustion engines have been fuelled by biomethane from municipal digester systems for more than 40 years with varying degrees of success [12]. Biogas produced from digesters can be used for two basic purposes. It can be burned directly for cooking and lighting or indirectly for lighting to generate electricity[12].

1.3. Problem statement

Energy is an important part of most aspects of day-to-day life of people. Hence, Ethiopia as developing country, despite its endowments with huge potentials of renewable energy sources such as hydropower, wind, geothermal, and bio-fuels, suffers from a severe domestic energy problem. This problem can be manifested by:

- ➢ Lack of reliable and affordable domestic energy sources
- ➢ Relatively very low per capita energy consumption
- ➢ Dominance of traditional biomass fuel use
- ➢ The existing problem of electricity in rural as well as urban area

Electricity problem exists in urban area is the main challenge in day-to-day income of the society, which utilizes electricity on their work.

Specifically the main problems distinguished in University cafeteria during cooking food:

- ✓ Cost of fossil fuel (gasoline and diesel fuel) during problem exist on electricity
- ✓ Problem occurs during traditional way of food wastes disposal and transportation, which is responsible for different diseases causing bacteria's and germs.

Factor driving for search in renewable energy is:

- ✓ Depletion and cost increment of non-renewable fuel
- ✓ Presence of CO_2 in biogas reduces the heating value of the gas
- ✓ Emissions of pollutant greenhouse gases (GHG) such as CO_2 and CH_4
- ✓ Increasing of global warming and an unexpected climate changes
- ✓ Health risk of due to presence of CO_2 and H_2S which is a poisonous gas
- ✓ Existing solid food waste potential

The key concern is to promote effective utilization of biogas cleaning and upgrading technologies for the purpose of clean, low cost and efficient power generation.

1.4. Objective of the research

The general objective of this study is to upgrade biogas for the purpose of electric power generation using chemical absorption.

1.4.1. Specific objective

- To produce methane enrich gas matching the standard of natural gas and remove contaminants using chemical scrubbing.
- To design biogas scrubber column to achieve a substantial contribution to future energy demands.
- To determine existing electricity potential generated from campus food waste
- To identify the financial benefits gain from biomethane production and fertilizer production.

1.5. Scope of the research

This research will give more attention to CO_2 absorption process, specifically using $Ca(OH)_2$ solution to produce methane enrich gas in addition NaOH is also used as a comparable chemical. Biogas cleaning such as moisture (H_2O) and Hydrogen sulphide (H_2S) removal using silica gel and activated carbon will be included in some extent. Emphasis is given to design scrubbing column, so as made test and validate the absorption process excluding chemical stripping process.

Food waste from Addis Ababa university student cafeteria is used as a substrate to conduct this research. Biogas digester is designed based on the amount of food waste collected from the cafeteria. In addition, the result gained from the experimental demonstration will validate with theoretical result using Matlab coding. After purification process, test biomethane on gasoline generator for the sake of electric power generation.

1.6. Significance of the research

Biogas upgrading has crucial role in order to use biogas in its higher energy content for generating clean, low cost, and efficient electric power. Biomethane helps the campus to be benefited from clean and non-exhaustible energy source. It serves as biofuel for backup electric generator when power from supply grid goes off.

If this thesis is, extend in to large-scale biogas upgrading technology it has Macro-Economic benefits through decentralized energy generation and environmental protection at country level. It increases the living standard of the society with an associate reduction of an increase use of fossil fuels. In addition it is significant in combating the growing emissions of GHGs. Therefore, it is essential to enhance technology transfer and to cope up with future sustainable energy demand.

1.7. Limitation

The design process of biogas upgrading is not a complete for an entire system. Instead, emphasis will put on completing a test model of the absorption system without including stripping process. This is due to the complexity of reversing NaOH solution. Lack of amine solution and $10m^3$ sizes of biogas gas kit in Ethiopia market is the major challenge during the thesis work.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Compositions of biogas

Biogas produced from anaerobic digestion of organic waste is mostly a mixture of methane (CH_4), carbon dioxide (CO_2) and smaller amounts of other gases and moisture, such as hydrogen sulfide (H_2S), ammonia (NH_3) and water (H_2O). Percentage composition of the gas and trace elements by volume is shown below[13].

Compound	**Chemical Symbol**	**Content (Volume %)**
Methane	CH_4	55 – 70
Carbon dioxide	CO_2	30 – 45
Water vapor	H_2O	2 – 6
Hydrogen sulfide	H_2S	<2

Table 2. 1: Composition of biogas in percentage by volume [14].

2.2. Biogas cleaning

Biogas cleaning is the process where any impurities are removed such as Hydrgen sulphides, water vapor and ammonia from raw gas. Before upgrading biogas using chemical scrubber it is necessary to clean and dry it using an adsorbent, which is crucial task to prevent damaging of internal parts of generator and pipe lines.

Adsorption process involves the transfer of gas stream to the surface of a solid material of adsorbent. where commercial adsorbents are exist generally in the form of granular solids or powder with a large surface area per unit volume[15].

2.2.1. Removal of Water Vapor

Biogas normally collected from moist substrate and the gas usually saturated with water vapor. This water may condensate in gas pipelines and cause corrosion. Moisture removal is especially important if the H_2S and CO_2 have not been removed from the biogas [16].

Need of removing moisture from Biogas:

- Presence of moisture in biogas to be used as fuel may corrode metallic parts of generator engine and fuel supply system.

- Also this moisture may react with SO_2.This reaction produces sulfuric acid (H_2SO_4) which may corrode engine pipe lines carrying exhaust gases and combustion system.
- Water vapor can react with CO_2 to form carbonic acid (HCO_3), which is a weak acid and corrosive as its pH become to near (5) five, which will readily attack metals.

Therefore, several methods are available while removing water vapor. It is possible to remove miosture from biogas either using condensation or using freshly prepared silica gel before passing through the H_2S removal unit.

A. Condensation

Water vapor from biogas can be removed by condensation techniques. Cooling is done either by increasing the pressure or decreasing the temperature of the gas, then water will condense from the gas and can thereby be removed by using condensate trap. Condensation can be achieved simply by burying and cooling the gas line equipped with a condensate trap in the moist soil.

B. Using silica gel SiO_2

On the other hand, water can be removed by adsorption technique using silica gel. It is a solid desiccant-drying agent. Silica gel is a chemically inert, nonflammable, non-toxic material composed of amorphous silicon dioxide (SiO_2). It has an internal network of interconnecting microscopic pores; water molecules are adsorbed or desorbed by these micro-capillaries until vapor pressure equilibrium is achieved with the relative humidity of the surrounding air[17].

It is hard adsorbent and is a crystalline substance, which is highly porous substance, can adsorb up to 40 percent of its own weight at 50% relative humidity (RH) and temperature at 25°C. Therefore, it has the highest water holding capacity than any of commercially available desiccant and have H_2O removal efficiency > 90%[13]. For well-sealed container, it is suggested that 200gram of silica gel is need for every meter cubic volume of package.

As silica gel started taking up moisture, they turned blue to pink gradually and became saturated as shown in figure 2.1 below. Then silica gel might be reactivated after saturation by heating it in an oven at 150℃ for 3 hours to remove the adsorbed H_2O[13].

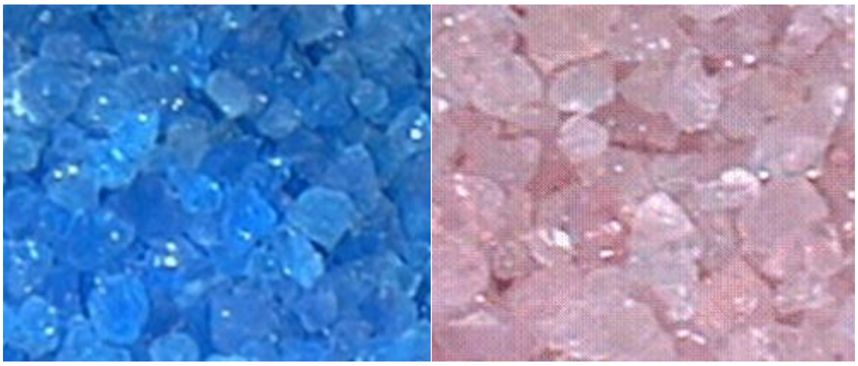


Figure 2. 1: Freshly prepared and Silica gel after moisture adsorption [16].

The tests were conducted with the controlled flow rate of biogas directly from the digesters at 1.5 l/min. The H_2O adsorption capacities by the silica gel and Na_2SO_4 used in the study were compared under variable time conditions [16].

The silica gel and Na_2SO_4 with in 220 min was capable of decreasing the H_2O-concentration of the gas approximately up to 0.2% and 1% for T_1 and T_2 , respectively.

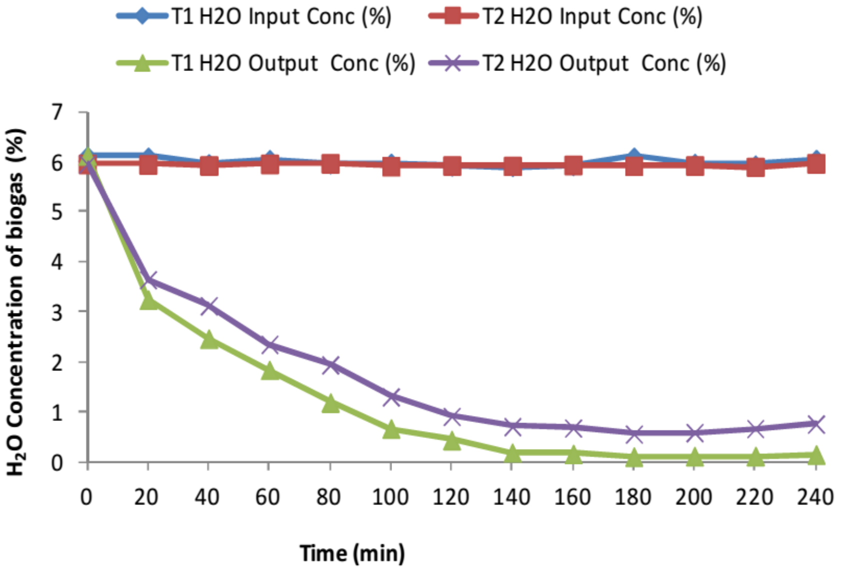


Figure 2. 2: Input and output H_2O-concentration of biogas for T_1 and T_2 [13].

2.2.2. Removal of hydrogen sulfide

Hydrogen sulfide is formed during microbiological reduction of sulphur containing compounds in this case food waste is one source of H_2S. The H_2S limit for electricity production by internal combustion engines is ≤ 100 ppm. Combustion of biogas containing H_2S produces (SO_2). When SO_2 combines with water vapor, it produces sulfuric acid (H_2SO_4) [18].

Need for H_2S removal from biogas:

It can cause serious corrosion in CO_2 scrubber unit, gas pipelines

- If engine is running using biogas which contain H_2S, its operating time to the first routine overhaul may reduce by 10 to 15%.
- Combustion of biogas containing H_2S produces gaseous sulfur dioxide (SO_2) also dissolves in engine oil causing the oil to become acidic and lose its ability to lubricate, damaging the engine and shortening time between oil changes.
- It is responsible for unpleasant odors and causes series disease, which leads to death.

There is variety of processes to remove H_2S.

A. H_2S removal by injecting air into the digester or biogas holder

When air is injected into the biogas digester, the thiobacilli bacteria, which is naturally, grow on the surface of the digestate oxidize H_2S. It reduces H_2S concentrations by as much as 95%. The injection ratio is typically from 2% up to 6% air to biogas ratio[15]. Then the by-product of this process is hydrogen and yellow clusters of elemental sulfur on the surface of the digestate[19]. This process is the most easily maintainable and the least expensive form of H_2S scrubbing. However, without careful control over the amount of air injected, this process can result explosion during mixing which cause accident and damage on digester [15].

The Claus process is used in removal of H_2S by oxidizing it to elemental sulfur. The following reactions occur in various reactor vessels and the removal efficiency depends on the number of catalytic reactors used:

$$H_2S + 3/2O_2 \rightarrow SO_2 + H_2O \quad \text{(2.1)}$$

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \quad \text{(2.2)}$$

$$H_2S + 1/2O_2 \rightarrow S + H_2O \quad \text{(2.3)}$$

The ratio of O_2-to-H_2S must be controlled strictly to avoid excess SO_2 emissions or low H_2S removal efficiency [15].

A. Adsorption using Steel wool/ Iron oxide

Another method to remove H_2S is making it to reacts with iron oxides in the form of oxidized steel wool or iron chips cut during lathe operation from any workshop to form iron supplied

[20]. Once biogas meets, steel wool/iron oxide reaction will be takes place and H_2S converts it into elemental Sulphur as shown in figure 2.3.

Figure 2. 3: Steel wool before and after H_2S adsorption process[14].

The gas to be filtered for purification enters from the bottom side of the chamber, passes through the ferrous absorbing agent and comes out from top of the vessel which will have reduced H_2S [17].

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.4)$$

$$Fe_2S_3 + 3O_2 \rightarrow 2Fe_2O_3 + 6S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.5)$$

It is a simple method but during regeneration, a lot of heat is released. In addition, the dust packing contains a toxic component and the method is sensitive to high water content of biogas. Approximately, 40 g of H_2S can be bound per 100 g of iron oxide chips [15].

A. H_2S removal using of activated-carbon

Another techniques of H_2S removal is using activated carbon, also called activated charcoal, it is a form of carbon that has been processed to make it extremely porous and thus to have a very large surface area available for adsorption or chemical reactions. It shows high affinity to polar substances such as H_2O, H_2S, SO_2 among many others. Activated carbon absorbs and decomposes H_2S to elemental sulphur[21].

Normally, activated carbons can exists either in powder or in particulate form. Powder activated carbons are fine granules less than 1.0 mm in size with an average diameter between 0.15 and 0.25 mm.

Granular activated carbon has a relatively larger particle size compared to powdered activated carbon and consequently, presents a smaller external surface.

Figure 2. 4: A Powdered activated charcoal (PAC) and Granular activated carbon (GAC)

According to Zicari at levels below approximately 200 ppm of H_2S, it has been shown that impregnated activated carbon beds from 20–25°C and atmospheric pressure can successfully remove up to 98% of the contaminant H_2S. Hydrogen sulphide loadings have been reported 0.5 g H_2S/g [22].

A typical H_2S adsorption capacity for impregnated activated carbons is 150 mg H_2S/g of activated carbon. A typical H_2S adsorption capacity for unimpregnated activated carbons is 20 mg H_2S/g of activated carbon. Therefore, H_2S removal efficiency of activated carbon is greater than 97% [13].

$$H_2S_{gas} + C \rightarrow H_2S_{ads.} + C \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

$$2H_2S_{ads.} + O_2 + C \rightarrow 2H_2O + 2S + C \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

According to Muhammad Rashid (2015) work removal of H_2S concentration of the tests was modulated by activated carbon and iron oxide T_1 and T_2 respectively. When the contact time was at 240 min and the flow rate is maintained at 1.5 l/min the H_2S-concentration was less than 50 ppm with respect to the initial concentration of H_2S in the gas for both tests as shown below in the Figure 2.5[13].

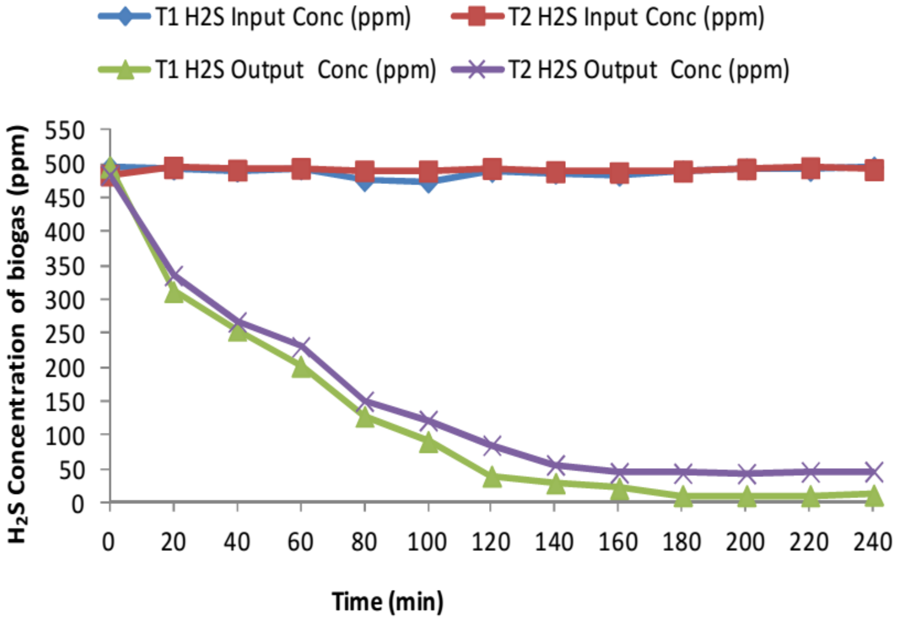


Figure 2. 5: Input and output H_2S-concentration of biogas [13].

2.3. Biogas Upgrading Technologies

Biogas upgrading on the other hand is the process in which carbon dioxide removal is performed and the end product is methane rich gas. Carbon dioxide is present in raw biogas with very high concentration. Its presence may result into reduced power output from the generator per unit mass /volume [23].

Natural gas predominantly consists of methane more than 90% and has a higher calorific value between the regions of 40–55 MJ/m^3. However, in the case of biogas the calorific value is between 20−22 MJ/.m^3 [24]. Therefore to extract the maximum thermal energy from biogas it is better to upgrade it into biomethane or in to the nearest quality of natural gas standard before beings used in place of petrol fuel [25].

Need for CO_2 Removal from Biogas:

- CO_2 removal from biogas improved thermal efficiency of the engine of the gas by more than 80% on a volume basis.
- CO_2 occupies additional space in storage cylinders requiring frequent refilling results into more energy consumption in compression of biogas.
- Presence of CO_2 can cause freezing problem at metering points and valves due to ice formation.
- Biogas upgrading is essential to increase use of biogas for wider range of applications.

There are a number of comercially available biogas upgrading technologies. Selection of the appropriate process for a particular application depends on the scale of operation, composition of the gas to be treated, degree of purity required, capital cost and the need for CO_2 recovery [6]. Commonly used and commercially available upgrading techniques discussed below.

2.3.1. Water Scrubbing:

Water scrubbing is the most common technique for removal of CO_2 from biogas. A water scrubber is a physical scrubber, which utilizes the difference in solubility in water for CH_4 and CO_2. Carbon dioxide which has a much higher solubility is absorbed by the water and hence separated from the raw biogas[26]. In order to achieve a good separation and to increase the driving force of solubility, a relatively high pressure is used in the column. Typically operating at pressures around 6-10bar [27].

$$CO_2 + H_2O \rightarrow H_2CO_3 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

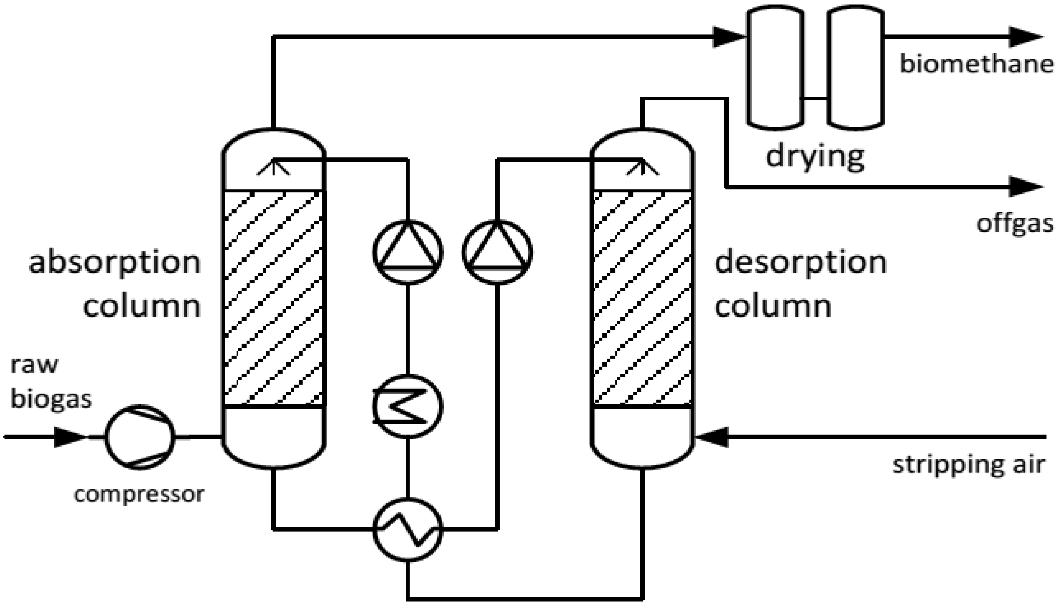


Figure2. 6: A process flow diagram for basic water scrubbing [15]

The CO_2 in the raw biogas absorbed by water and an upgraded gas stream with high methane concentration leaves the top of the column. The rich water is sent to a flash tank where the pressure is abruptly reduced to pressures around 2.5-3.5 bar. It is possible recycle the water.

2.3.2. Organic physical absorption

Organic physical absorption is similar to water scrubbing. Nevertheless, the difference exists that organic solvents are applied as scrubbing liquid such as; Selexol. The advantage of applying this solvent is the increased solubility of CO_2, compared to that of water, and more environmental friendly compared to amines and NaOH solution[28]. Heating is needed before the solvent is fed to the desorption column, and then cooled before entering the absorption column[6].

2.3.3. Pressure Swing Adsorption

This technique separates different substances on the basis of physical forces and molecular size, which dictates the penetration ability in a material. The driving force of the separation is pressure differences, where CO_2 is absorbed at high pressures and desorbed at low pressures. The alteration between high and low pressure leads to an effective absorption/desorption process[29]. A major advantage of the process is the dry separation without the use of a solvent. Hence, no additional water is added in the process. Raw biogas from SFW is compressed to elevated pressures and fed to an absorption column witch retains the CO_2 but not the methane [6].

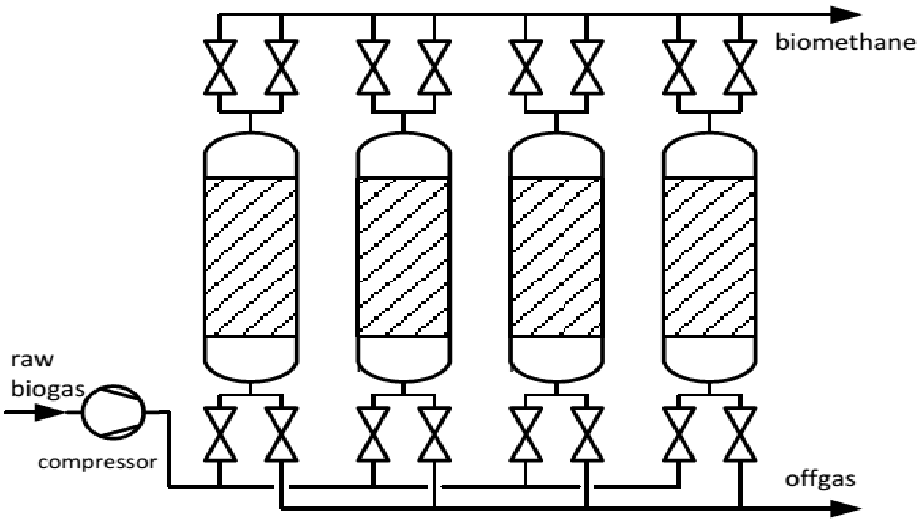


Figure 2. 7: A process flow diagram for basic pressure swing adsorption, from [3]

2.3.4. Membrane Technology

Membranes for biogas upgrading are made of materials with low permeability for methane and high permeability for compounds to be separated such as CO_2. Very little methane normally escape through the membrane [29]. The membrane is a physical barrier through which most of the easy permeable compounds are separate from the less permeable [30]. Methane is restrained, while carbon dioxide passes through the fiber wall in the membrane. Water and hydrogen sulfide are usually removed from the raw biogas, before being compressed and fed into the membrane [6].

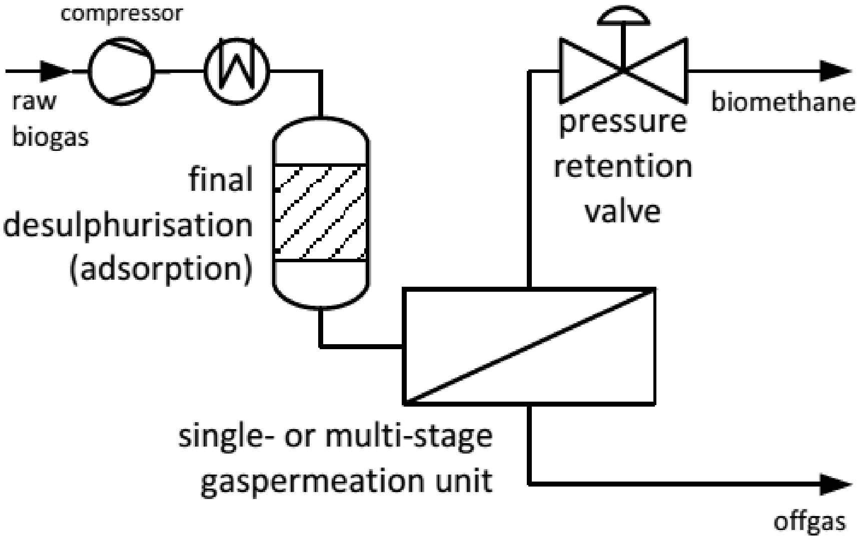


Figure 2. 8: A process flow diagram for basic membrane technology[15].

Biogas from FW should be compressed up to its operating pressure typically around 6-20 [bar].

2.3.5. Cryogenic separation

Cryogenic upgrading involves condensing various components of the biogas. Biogas is cooled down until some of its constituting components turn into liquid. This method can be used if the components in the gas have different condensing temperatures. Methane has a condensing temperature of -161.5°C in atmospheric pressure, while carbon dioxide has a condensing temperature of -78.4°C [31]. If biogas is cooled to -78.4°C, carbon dioxide begins to condense and can be removed in a liquid form [6].

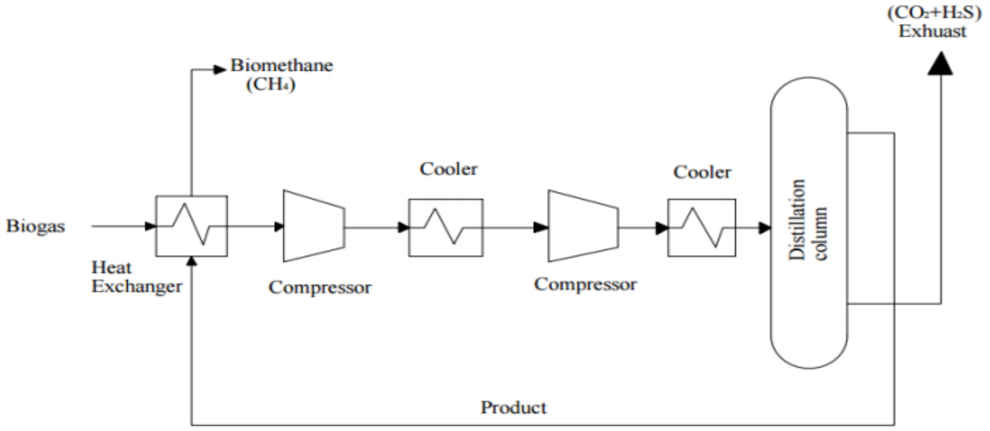


Figure 2. 9: Cryogenics Separations[15]

2.3.6. Chemical Absorption

Chemical absorption is characterized by a physical absorption of the CO_2 gas in a scrubbing liquid, followed by a chemical reaction between scrubbing liquid components and absorbed gas components within the liquid phase. It is based on the reactivity of the chemical reagent used as absorbent to chemically react with the carbon dioxide molecule. Thus remove it from the biogas feed stream[15].

The absorption involves formation of either reversible or irreversible chemical bonds between the solute and the solvent. If it is reversible chemical reaction, regeneration of solvent is possible unless regeneration of the solvent become impossible. Regeneration involves breaking of these bonds correspondingly due to application of a relatively higher energy input. Most of the time aqueous solutions of amines (i.e. mono-ethanolamine) solution is primarily employed as chemical absorbent during scrubbing process. Alternatively, it is possible to use aqueous solution of sodium, potassium and calcium hydroxides.

The chemical scrubbing of CO_2 was performed in a counter current flow using column reactor packed with different types of packing.

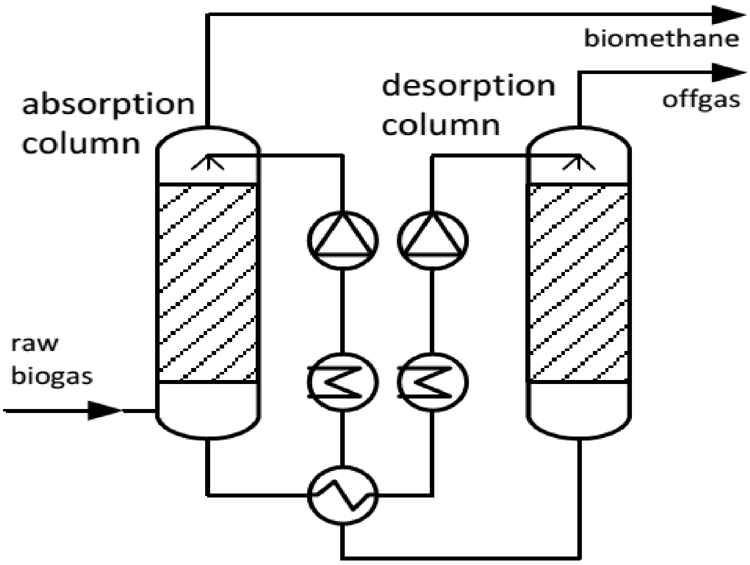


Figure 2. 10: A process flow diagram for Chemical scrubber technology[15].

According to (Biswas 1977), those who did experimental work using biogas bubbling with the ten percent solution of mono-ethanolamine. Hence, He observes decrease in carbon dioxide from 40% to 0.7%. An important advantage of using MEA is that it can be reutilized after boiling it for five mints[18].

2.4. Comparison between upgrading technique

All of the upgrading techniques mentioned here have the ability to upgrade biogas above 95% CH_4 content. However, all technologies have their own specific merit and demerit. There is no technology, which is the optimal solution to each biogas-upgrading process. In order to select the appropriate biogas upgrading technique for any given situation careful consideration should be made on the following criterion [15].

- Achievement of greater operational efficiency for the requirements of CH_4 purity,
- Minimization of CH_4 losses or CH_4 slip from economic perspective,
- Ecological reasons, environmental issues regarding disposal of hazardous byproducts,
- Ability of the system to operates under no significant pressure and temperature,
- The possibility of solvent to be regenerated and the overall cost of plant.

During water scrubbing process, large amount of pressure is required as it is compared with chemical scrubbing technique. This technique is not suggested, when the compositions of the hydrogen sulfide is high, since the water can turn out to be polluted with plain sulfur which can cause operational troubles [18]. Degree for CH_4 purity during water scrubbing is relatively less than chemical scrubbing.

In the case of pressure swing adsorption, the process requires additional separate mechanism or set up for the removal of hydrogen sulfide and moisture. Its major disadvantage is that need high pressure as it compared with chemical scrubber [15].

Membrane separator uses simple technique, but the problem with the cost of the membranes, which is highly costly.

The major drawback of cryogenic separation is that it involves the use of several equipment and devices, such as compressors, heat exchangers, turbines, insulators, and columns. In addition, it require very high pressure to create lower temperature below -162 ℃. Therefore it needs high investment cost as it compared with other scrubber [15].

It is therefore advantageous to have an optimized upgrading process based on low energy consumption and high efficiency on delivering high methane content after upgrading process. It is also very important to reduce or eliminate methane slip during upgrading process. Therefore, based on the above criterion and selection method chemical scrubbing technique is the best choice as the subject of this thesis work [18].

2.4.1. Benefits of using Chemical scrubber

- ✓ It can operate at normal pressure and temperature,
- ✓ Gas contains higher rates of purity than other conventional systems
- ✓ Stable process of purification and can deliver constant quality of methane
- ✓ Have comparatively low operational cost

2.5. Selection of appropriate chemical Solvent

During chemical absorption, solvent selection is the most crucial step before the upgrading process takes place. The suitability of a solvent to be used for absorbing CO_2 from biogas is decided by the difference in solubility between CO_2 and methane in that solvent[9].

To do this there are basic requirements used as a parameter such as solvent availability, price, environmental friendly, having a high CO_2 load, less corrosively to absorption equipment, easy to regenerate, and having low viscosity.

Most of the time chemical absorption process operates by using amines solution. However, in these theses caustic solvents is selected because of the reason mentioned below:

- Major challenge when implementing amine scrubbing for CO_2 removal is its highly corrosive nature. Some amines, such as MEA, have high corrosive nature[9].
- The main problem exists that the amine solution is not available in local as well as national market in Ethiopia.

Caustic solvents (sodium hydroxide, potassium hydroxide, and calcium hydroxide) are the second most abundant solvents which can chemically absorb CO_2 from a mixture of gases after amine solutions.

Even if potassium hydroxide (KOH) solution has the fastest chemical reaction with CO_2 it is not preferable to use as an absorbent because of its high cost and it require high caution during the process. Therefore, comparison is made between NaOH and $Ca(OH)_2$ solution. Similar to amines, other than being physically absorbed, NaOH and $Ca(OH)_2$ chemically absorbed CO_2 via the reaction given in Equation 2.7 and 2.8 [16].

$$2NaOH(aq) + CO_2(g) \rightarrow Na_2CO_3(aq) + H_2O(l) \ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

$$Ca(OH)_2(aq) + CO_2(g) \rightarrow CaCO_3(aq) + H_2O(l) \ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

Absorption of biogas with NaOH and $Ca(OH)_2$ is a two-stage process. The first stage is the actual CO_2 absorption using caustic solution and the second is stripping process, which implies CO_2 extraction from the liquid absorbent in order to reuse it. However, as mentioned earlier this paper will focus only on absorption process because the complexity of the process and the irreversible nature of caustic solvent[16].

The design will focus on upgrading biogas by utilizing chemical scrubbing specially using calcium hydroxide $Ca(OH)_2$ rather than sodium hydroxide (NaOH) [16]. Sodium hydroxide were served as a second most abundant solvents better than calcium hydroxide $Ca(OH)_2$, but its cost is higher than that of $Ca(OH)_2$ because of its cost and due to the reason that is listed below $Ca(OH)_2$ is became suitable:

- ✓ Possess a greater CO_2 loading capacity
- ✓ Produce high quality biomethane
- ✓ Less costly than many other methods,
- ✓ Requires no sophisticated control instruments to run, and
- ✓ More available

According to M.A. Olutoye (2017) work, the highest level of methane (89.3%) was achieved by using a calcium hydroxide solution of 0.2 mol. with a gas flow rate of 5 l/min. and a solution flow rate of 30 l/min. Therefore, it was found that this treatment could increase the amount of methane when the solution flow rate was high, but when the biogas flow rate was low. In other words, the biogas and solution flow rate can affect the biogas treatment efficiency[32].

Aqueous solutions of NaOH and $Ca(OH)_2$ were used as chemical solvents to demonstrate the ability to absorb CO_2 represented by T1 and T2 respectively. The reactor flask was observed to gradually remove high proportion of CO_2 resulting in CH_4 enriched biogas [16]. The CO_2-concentration of biogas decreased gradually 40% to 3.6% and 4.6% at 240 min treated in T_1 and T_2, respectively as shown below in the Figure 2.10.

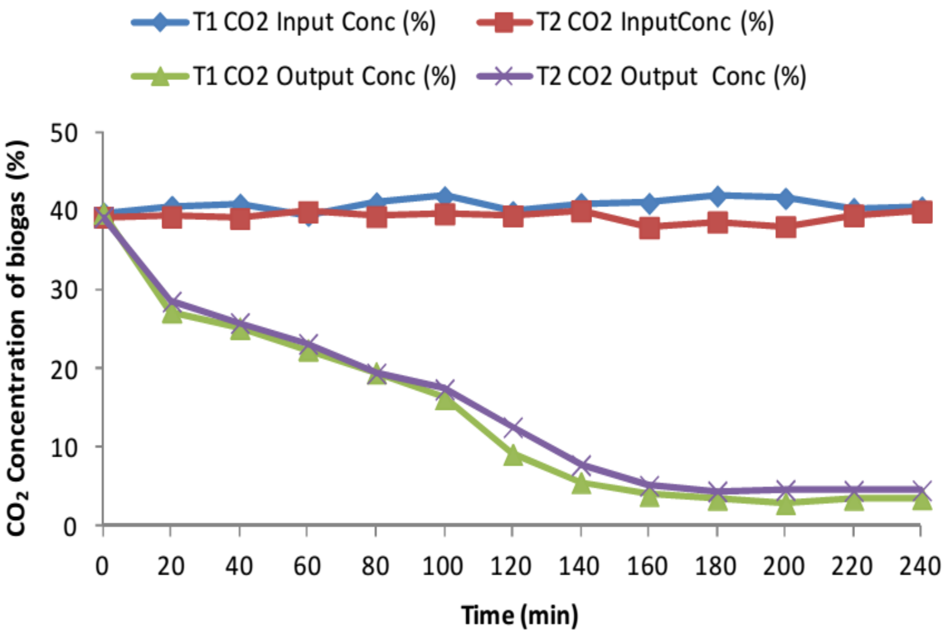


Figure 2. 11: Input and output CO_2-concentration of biogas for T1 and T2[13].

2.6. Application of biomethane

Biomethane is an excellent solution to substitute traditional fuels, such as firewood, dung cake and even kerosene, which are used for heating purpose. It provided clean, low cost and efficient energy and increases the living standard of the society with an associate reduction of an increase use of biomass and fossil fuels, which is significant in prevent associated health risk and combat the growing emissions of GHGs[33].

Biomethane can also utilize as source energy to drive electric generator and water pumps in place of fossil fuel. It is helpful during electrification and irrigation to the agricultural sector. In addition, it serves as source of energy in place of gasoline and diesel fuel to operate electric generators at small scale for the purpose of backup electricity generation when there is electricity problem in urban center [34].

Depending on the end use, different biogas treatment steps are necessary. For some applications, where it is important to have a high-energy content in the gas, e.g. as vehicle fuel or for grid injection, the gas needs to be upgraded [35].

It is applicable either for internal combustion engine or for external combustion engine. Combustion engines are popular as they are more efficient and less expensive. Internal combustion motors have become the standard technology either as gas or diesel motors in most commercially run biogas power plants [25].

In case of electricity generation, it serves as a heat source of for boiler to produce steam for the sake of rotating steam power plant. This is applicable from small scale up to large scale. Biomethane can operate efficiently in a cogeneration or Combined Heat and Power (CHP) technology with an efficiency of up to 89% and produces heat and electricity simultaneously [35].

CHAPTER THREE

3. MATERIAL AND METHODOLOGY

3.1. Materials

The data inputs for the research were gathered both from primary and secondary sources. Primary data were collected through personal observation. The study was conducted for 8 weeks from January 2 to February 29, 2017, which was necessary to classify food waste based on their types and weight measurement was taken. Whereas, secondary data were gathered from different published sources including books, journal, articles, and internet.

3.1.1. Data collected from Addis Ababa Sidist Kilo Campus, AAU

Food waste obtained from student cafeteria is taken as a feedstock to conduct experimental evaluation on biogas upgrading. Data need here is total food waste in kg thrown per year. A quantitative sampling technique was done on campus food waste. Data were collected from one of the cafeteria in the campus. Three types of food samples are chosen during the data collection period. Sample size taken for the Enjera with wot was 100kg , for bead and wot only was 6kg and 7kg respectively.

1. Enjera with Wot (kg)
2. Bread (kg)
3. Wot only (kg)

Material used for sampling

- Weight balance (beam balance scale)
- Hand entry data sheet
- Plastic bucket
- Plastic hand glove

According to Castro-Garcia (2006) recommendation quantification of wasted food waste are on-site measurements and food waste” monitoring by diary were employed [36]. Six individuals were involves during data collection three of them gathered the waste, identified its content and the rest three of them measured the amount, and recorded the quantity. Each team reported their data daily. Waste was sampled very early in the morning prior to scheduled collection times at the selected site. Three category food wastes were selected to be studied. Each waste category was measured from between the campus cafeteria for 8 weeks. In addition, interview also done with manager of the cafeteria.

Procedure during data collection

1. Three plastic buckets with 10 liter volume were used to store food waste during measurement. Then mass of plastic bucket were measured alone and were recorded.
2. Most of the time during breakfast bread became more abundant food taste. And Enjera with wot became more abundant during lunch and dinner.
3. Sampling took place immediately after the selection of types of food waste.
4. Food wastes are separated using glove and putted in each buckets separately based on their types.
5. Then mass of food waste with the bucket were measurement after the bucket reach at its maximum level and the measured data being recorded on hand entry data sheet.
6. Finally, mass of food waste demined by subtracting mass of the bucket from the total mass and recorded as shown in appendix 5.
7. This was done on daily basis for two months. Daily mean value of food wastes were calculated using sample mean formula from statistical analysis.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Besides the mean, the next most important moment is the variance, which measures the dispersion or spread of random variable x about its mean and calculated using standard deviation formula shown below:

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

The purpose of the sampling here is to estimate amount of waste generation rates rather than more global measures, and to analyze the data with the application of rigorous statistical analyses. The standard deviation for Enjera with wot is 2.75 for bread and wot only is 0.756 and 0.748 respectively.

Types and amount of food waste collected from one of the student cafeteria is presented in table 3.1 as shown below.

Days	**Food waste**		
	Enjera with Wot(kg)	**Bread(kg)**	**Wot only (kg)**
Monday	100	5	7
Tuesday	105	7	6
Wednesday	101	6	6
Thursday	100	5	5
Friday	105	6	7
Saturday	100	5	6
Sunday	110	7	6
Total	**721**	**41**	**43**

Table 3. 1: Total amount of Enjera with Wot, Bread, and Wot only collected from student cafeteria (Source: field survey, 2017)

Item No.	**Food type**	**Total (kg)**	**In (100%)**
1	Enjera with Wot	721	89.56
2	Bread	41	5.09
3	Wot only	43	5.34
Total		**805**	**100**
Average		**115**	**-**

Table 3. 2: Average weight of food waste collected for each day from the student cafeteria (Source: field survey, 2017)

According to the collected data, 115kg of food waste per day and 41,975kg of food waste per year was simply thrown into garbage container.

3.1.2. Instruments used:

During the experiment, different instruments were used for the purpose of biogas production and upgrading. Instrument used for sample test:-

- **Weighing Scale**: is used to measure mass of food wastes
- **Portable Gas Analyzer**: measure the chemical composition of biogas and composition of purified gas after upgrading takes place.
- **Biogas gas kit:** holds the purified gas (biomethane) for chemical analysis and the test.

- **pH Meter**: measure pH value of the food wastes during biogas production and scrubbing solution before and after chemical scrubbing takes place. The food wastes have pH of 7.50.
- **Digital Thermometer**: is used to measure temperature of biogas digester during biogas production and temperature of chemical solution before and after CO_2 absorption. The thermometer was in the range of 0 °C to 100 °C.
- **Pressure gauge**: uses to measure gas pressure up to 8bar.

Instrument used for digester construction and build scrubber column:-

- ✓ **Biogas digester:** is an enclosed area where the substrate is stored and anaerobic digestion takes place. To do this $10m^3$ Roto tanker made of fiberglass is used.
- ✓ **Circular tube (HDPE pipe):** serves as in place of water bass to maintain digester temperature at its mesophilic condition.
- ✓ **PPR Valve**: uses to control gas flow rate through the pipe.
- ✓ **PVC pipe:** one 110mm diameter and 2.20m long PVC was used as to build CO_2 scrubber to allow liquid ($NaOH_{(aq)}$) and $Ca(OH)_2$ solution.
- ✓ **PPR pipe:** two 50mm diameter and 30cm long PPR pipe was used; the first one is either to hold activated carbon or steel wool for the sake of H_2S removal and the second one is either to hold silica gel or sodium sulfate with the objective of moisture removal. This two pipes are connected each other by half inch PPR pipe.
- ✓ **Tyre tube:** used to store purified gas

Device used to transport fluid:-

- **Pump:** is used to pressurize water and liquid chemicals absorber during biogas production and upgrading time respectively.
- **Compressor:** is used to pressurize biomethane gas to assist flow in to the required level.

Chemicals used to clean and upgrade biogas:-

- ✓ **Sodium hydroxide (NaOH) and calcium hydroxide $Ca(OH)_2$:** used to remove CO_2 gas.
- ✓ **Activated carbon (C) and steel wool:** is used to remove H_2S from row biogas.
- ✓ **Silica gel (SiO_2) and sodium sulfate ($NaSO_4$):** is used to remove moisture (H_2O) from the raw gas.

3.2. Method Used

Process flow diagram shows the overall system from biogas production up to power generation as shown below in figure 3.1.

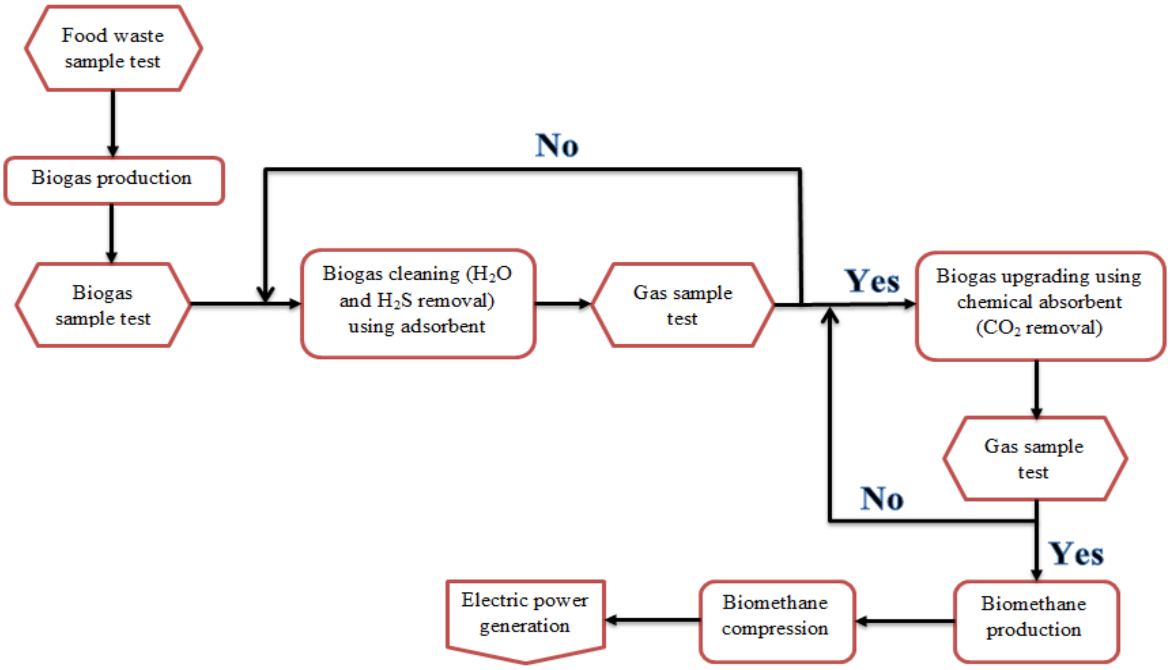


Figure 3. 1: Flow system from biogas production up to power generation using block diagram

3.2.1. Kinetic modeling of anaerobic digestion

From the figure 3.2, a well-mixed digester tank contains a mixture of solid food waste A and water B at a certain ratio. Once in the digester, the substrate A and B break down into products gas C and D at a rate based on biochemical reaction comes out through the top of the digester. Some of A and B do not break down all the way, rather it leaves through the bottom section of sludge outlet. The amount sludge that leaves digester depends upon reactor size and feeding rate, which determine the feed time of the substrate.

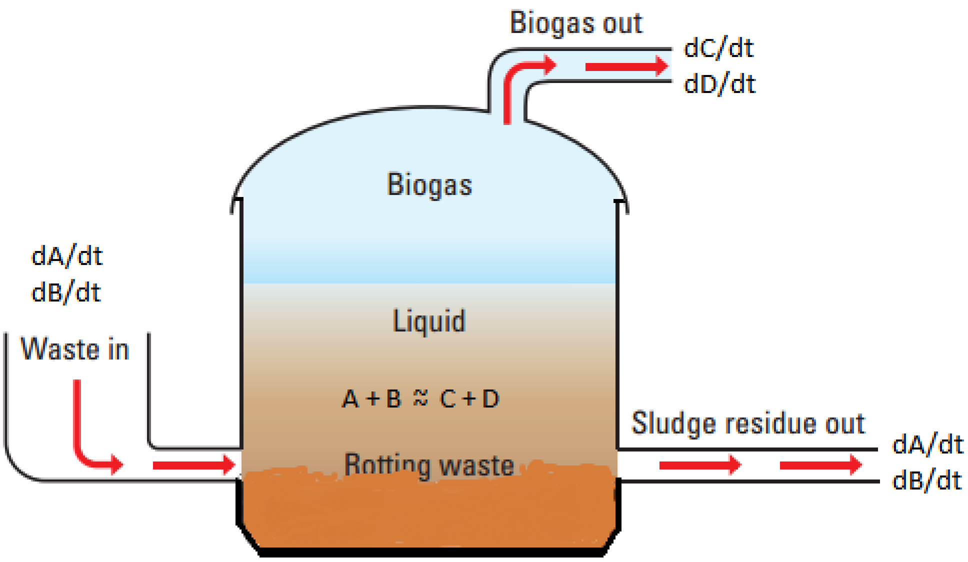


Figure 3. 2: Basic input-output model of a digester tank[37]

3.2.2. Elemental analysis of food waste for biogas production

This analysis is done by taking one gram of dry food waste sample in to Addis Ababa Arat Kilo University chemical department. Then food waste broken down in to elemental composition of carbon, hydrogen, oxygen, nitrogen and sulfur then after their percentage composition were measured. The elemental analysis of food waste will help us identify chemical composition of the food waste as shown in the table below.

FW Elemental Composition	%
C	45.405
H	7.655
O	42.915
N	3.945
S	0.4

Table 3. 3: Elemental analysis of food waste (Source from laboratory measurement)

3.2.3. Biochemical Equation of biogas production process

The initial assumptions of the system are listed as follows.

- Constant digester temperature
- Constant digester volume
- Perfect mixing
- Ideal bacterial conditions, meaning full digestion is takes place
- Products of reaction include only CO_2 , CH_4 , H_2S and NH_4
- No accumulation of ashes

The biochemical reaction equation used for this analysis is shown below:

$$C_nH_aO_bN_cS_d + c_1H_2O \rightarrow c_2CO_2 + c_3CH_4 + c_4NH_3 + c_5H_2S \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

The biochemical reaction is balanced as shown in the table 3.4 below and can be applied to any input with known relative ratios of carbon, hydrogen, and oxygen [38]. The model assumes that these elements are the only components of the feedstock.

	Left	Right
C	.n	n/2 + n/2 = n
H	a + 2*[n – a/4 – b/2 + (3/4)*c + d/2] = 2n + a/2 - b + (3/2)*c + d	4[n/2 + a/8 - b/4 - (3/8)*c - d/4] + 3c + 2d = 2n + a/2 -b + (3/2)*c + d
O	b + [n – a/4 – b/2 + (3/4)*c + d/2] = n –a/4 + b/2 + (3/4)*c + d/2	2*[n/2 – a/8 + b/4 + (3/8)*c + d/4] = n –a/4 + b/2 + (3/4)*c + d/2
N	.c	.c
S	.d	.d

Table 3. 4: Balance of biochemical reaction

The mol ratios and coefficient of each reactant and product can be calculated using the equations shown below:

$$M = nm \text{………………………………………………………}(3.2)$$

M = molar mass of reactant and product

n = number of mole

m = mass ratio

Detail chemical analysis included in the mat-lab code, which encompasses determination of mole ratio and coefficient of the above chemical equation.

❑ Biogas upgrading Matlab algorism

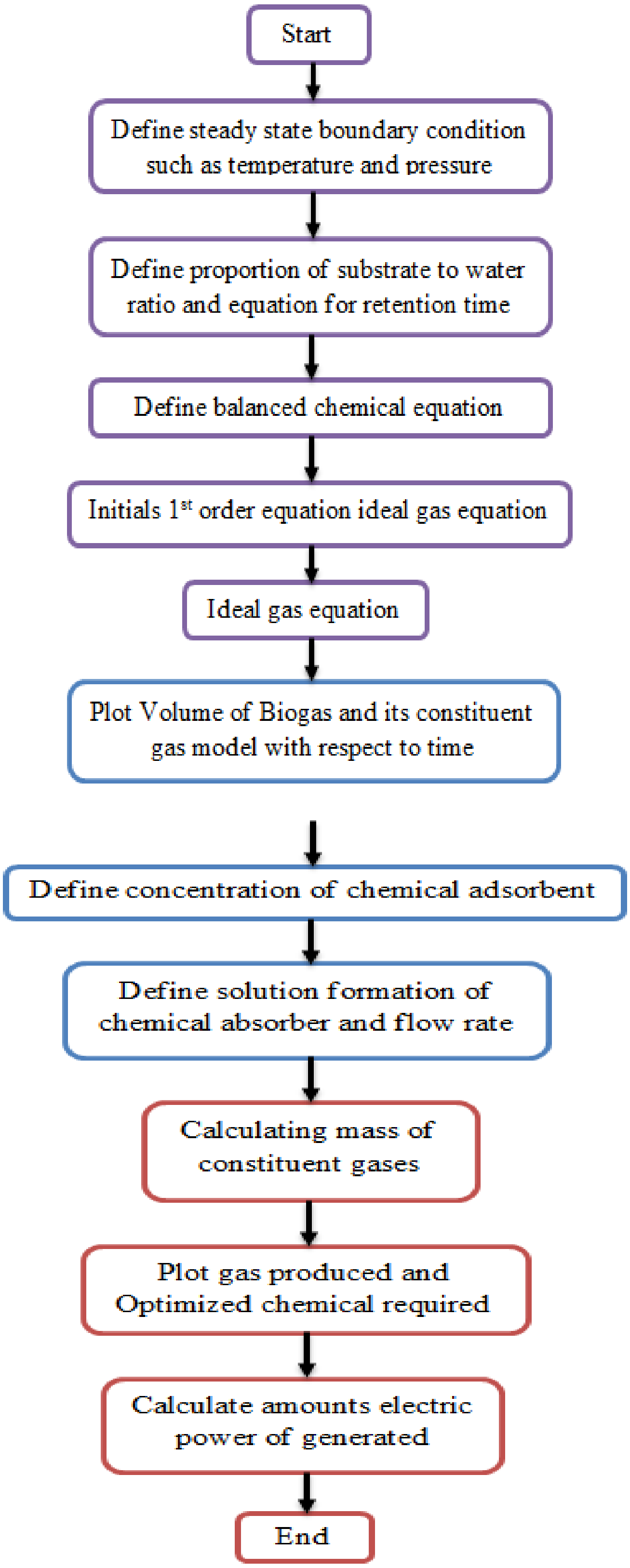


Figure 3. 3. Matlab algorithm from biogas production to electricity generation

3.2.4. Preparation of chemical solvent

Aqueous solution of NaOH and water within 10:90 ratios by weight is prepared in a container. During mixing of NaOH and water, enormous amount of heat is generated due to exothermic reaction exist between them. When heat is disappeared, it is pumped to the top of the scrubber which contains shower cap for the sake of uniformly distribute and increase the surface contact between the gas and liquid solvent inside the column. In case of NaOH solution, solvent preparation can be expressed by the following equation:

$$\mathrm{NaOH_{(solid)} + H_2O_{(liquid)} \rightarrow NaOH_{(aqueous)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

$$\mathrm{2NaOH_{(aq)}\ +\ CO_{2(g)}\ \rightarrow\ Na_2CO_{3(aq)}\ +\ H_2O}_{(l)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

The same procedure need to be followed for the case of $Ca(OH)_2$ solution. The solution of limestone and water in 10:90 ratios by weight can be prepared in a container. When limestone and water are mixed together, enormous amount of heat will be generated due to exothermic reaction.

$$\mathrm{Ca(OH)_{2(s)}\ + H_2O_{(l)} \rightarrow Ca(OH)\ _{2(aq)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.5)$$

$$\mathrm{Ca(OH)_{2(s)} + CO_{2(g)} \rightarrow CaCO_{3(aq)} + H_2O}_{(l)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

3.3. Experimental set up

The experimental set-up consists of three sections; the first section is a metabolism section generating the desired amount of biogas in ten-meter cube ($10m^3$) fiberglass roto using food as a substrate. The second section is cleaning section, which consists of one (PPR) plastic scrubber (W1) filled with either by 500g of silica gel or 500g sodium sulfate respectively for moisture removal. In addition, one (PPR) plastic scrubber (S1) filled with either by 500g activated charcoal or 500g steel wool/iron chips for H_2S removal.

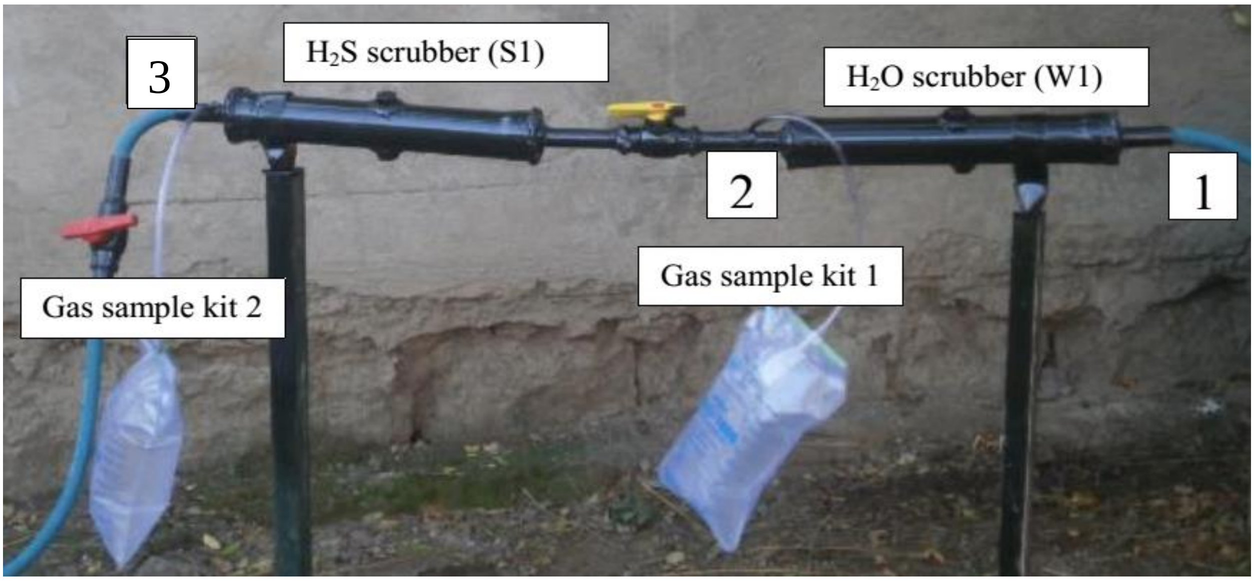


Figure 3. 4: Moisture and H_2S scrubber unit filled with silica gel and activated carbon respectively.

The third section is upgrading section, here the unit consists of one 2.4m long and110 mm diameter scrubber (U1) which is made from PVC pipe important to create contact between biogas and chemical solution it might be aqueous solution NaOH or $(CaOH)_2$ for the purpose of CO_2 absorption as shown in the figure 3.4 below.

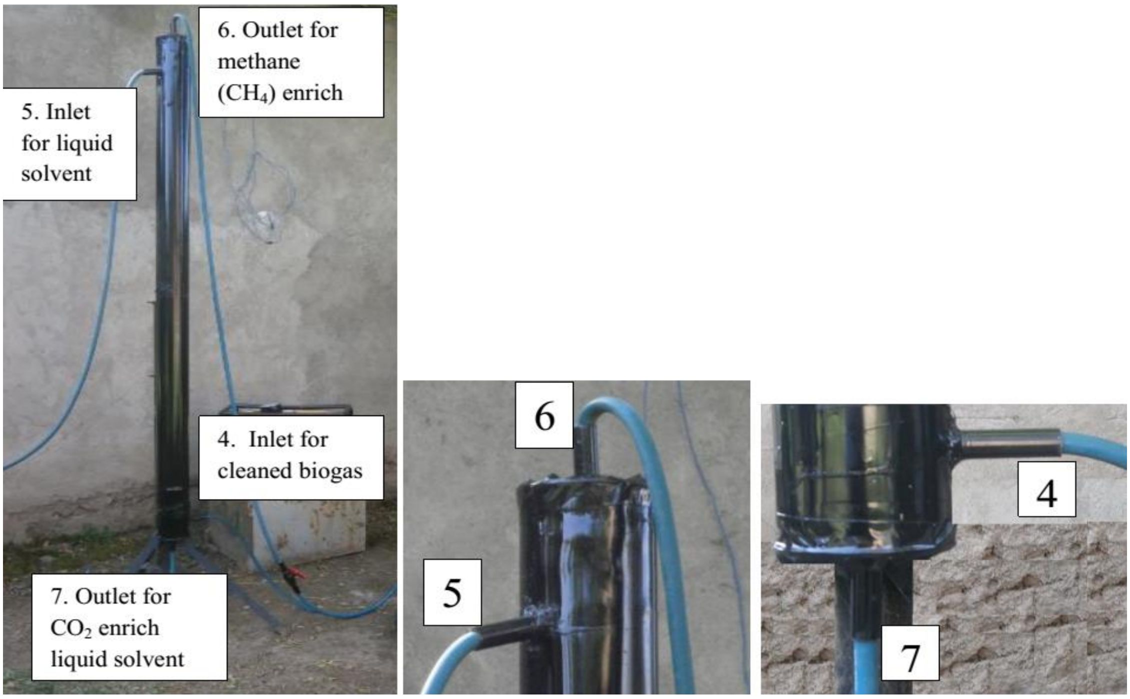


Figure 3. 5: Input and output system of CO_2 scrubber column

Experimental procedure during biogas purification

Step1. Sample gas was taken from biogas digester using gas kit, then chemical analysis is done here percentage composition of biogas is measured and recorded.

Step2. Then moisture scrubber W1 was interconnected with the digester by 2m long plastic hose. After connecting the hose, raw gas is introduced through a tubing at point 1 in to W1, which consists of moisture adsorbent. Then measurement was performed by taking sample.

Step3. After moisture removal, the dry gas enters in to S1, which was connected with moisture scrubber by 0.40m long hose controlled by gate valve as shown in figure 3.4 at point 2. Then H_2S gas was adsorbed either by activated carbon or by steel wool/iron oxide. Then measurement was done again by taking sample.

Step4. After cleaning process, purified gas enters in to CO_2 scrubber U1, which is connected by 3m long hose. Biogas fed in to the absorber at its bottom section represented by point 4. In addition, liquid chemical solvent enters in to the scrubber at its top position shown in in figure 3.4 at point 5. There was direct contact between gas and chemical absorbent to remove CO_2. Then, methane rich gas comes out through the top section indicated by point 6.

Step5. Finally, purified gas were compressed and stored in to plastic tyre tube and chemical composition test was performed using portable gas analyzer. After purification and compression, biomethane flow through a pipe in to the generator forced by the action of tyre tube.

Figure 3. 6: Storing biomethane in to tyre tube

The generator converts the supplied fuel energy from chemical to mechanical energy finally generate the required power.

Figure 3. 7: Overall procedure of biogas upgrading and electricity generation

CHAPTER FOUR

4. BIOGAS PRODUCTION AND DIGESTER DESIGN

Biogas is the result of the anaerobic digestion (AD) process, in which anaerobic bacteria degrade organic materials. The nature of the raw materials and the operational conditions used during AD, determine the CH_4 concentration and other chemical compositions of the biogas. The main compositions of the biogas derived from biomass, sewage digester, landfills, and food waste etc.

4.1.1. Factor affecting biogas production

There are many factors affecting the AD process and the quantity of produced gas inside the digester. Any drastic change in these factors can adversely affect the biogas production. So these parameters should be adjusted within the desirable range to operate the biogas plant efficiently [39].

pH value: The survival of methanogenic bacteria also depends on the acidity of the environment. They require a near-neutral pH (between 6.5 and 7.5) [39]..

Temperature: Temperature is one of the basic parameters that affect the survival of the bacteria inside the digester. The three digestion types of temperature ranges are named psychrophilic, mesophilic and thermophilic digestions [40].

Digester temperatures	Psychrophilic	Mesophilic	Thermophiles
Operating Temperature (°C)	0 – 25	25 – 45	45 – 65

Table 4. 1: Temperature ranges for anaerobic digestion

Total Solid: The total solid (TS) test determines how much of the food waste is composed of water and how much of the food waste is solid[41]. The samples were then placed in an oven set to 105°C for a period of at least 24 hours and weighed until there was no change in weight[42].

Volatile Solid: The sample, which was dried in the total solid method, is placed in a furnace at a temperature of 550°C for at least 4 hours. This test determines how much of the dry matter is composed of volatile organic material. The resulting residue is composed of inorganic material[39].

C/N Ratio: The production of biogas can also be influenced by the relative amount of organic carbon and nitrogen in the feedstock, which is measured as Carbon/Nitrogen (C/N) ratio.[43] A low C/N ratio can lead to pH values above 8.5, while a high C/N ratio may result in lower methane production rates[39].

Mixing: Contact between bacteria and the slurry that they are consuming is vital to the anaerobic digestion process. One way to maximize this contact is to keep the digester thoroughly mixed at all times [39].

Hydraulic retention time (HRT): Most anaerobic systems are designed to retain the waste for a fixed number of days. The number of days the materials stays in the tank is called the hydraulic retention time. The required time for complete digestion of the substrate inside the digester depends on the type of the substrate, substrate particles size, stirring and mainly on the temperature of the digester [39].

4.2. Biogas production potential of various wastes

Using AD biogas can be produced from various types waste such as cow/cattle dung, vegetables/agricultural waste, droppings of poultry farm, industrial waste water, and municipal solid waste/sewerage waste, and landfill etc. Biogas production potential from various wastes and methane content is shown below in table 2.

Raw material	**Biogas production Liters/kg**	**Methane content in biogas (%)**
Cattle dung	40	60
Green leaves and twinges	100	62
Food waste	90	65
Bamboo dust	53	71.5
Bagasse	330	56.9
Dry leaves	118	59.2
Non edible oil seed cake	242	67.5

Table 4. 2: Biogas Production Potential from Various Wastes[14]

4.2.1. Biogas production calculation

Amounts of gas produce per day

Let RT $=$ 30 days, where RT= Retention Time

Total solid TS $= 33.03\%$

Volatile solid VS $= 26.64\%$

Daily Input $= 115\ \mathrm{kg/day}$

$$\text{TS of fresh input} = 115\ \mathrm{kg} \times 0.3303 = 34.88\ \mathrm{kg}$$

In 9% concentration of TS (to create a favorable condition to AD of the food waste)

Total influent required = Q

$$Q = \frac{34.88\mathrm{kg}}{0.09} = 387.55\mathrm{kg}$$

Water to be added to make the discharge 9% concentration of TS

$$W_{add} = 387.55\mathrm{kg} - 115\ \mathrm{kg}$$

$$= 272.55\ \mathrm{kg}$$

Amounts of biogas produced in each day:

$$\text{Biogas produced per day} = 0.09\mathrm{m}^3 \text{ of biogas/kg of food waste} \times 115\ \mathrm{kg/day}$$

$$= 10.35\mathrm{m}^3/\mathrm{day}$$

Amounts of gas produce per year

$$\text{Biogas produced per year} = 10.35\mathrm{m}^3/\mathrm{day} \times 365\ \mathrm{day/year}$$

$$= 3{,}777.75 m^3/\mathrm{year}$$

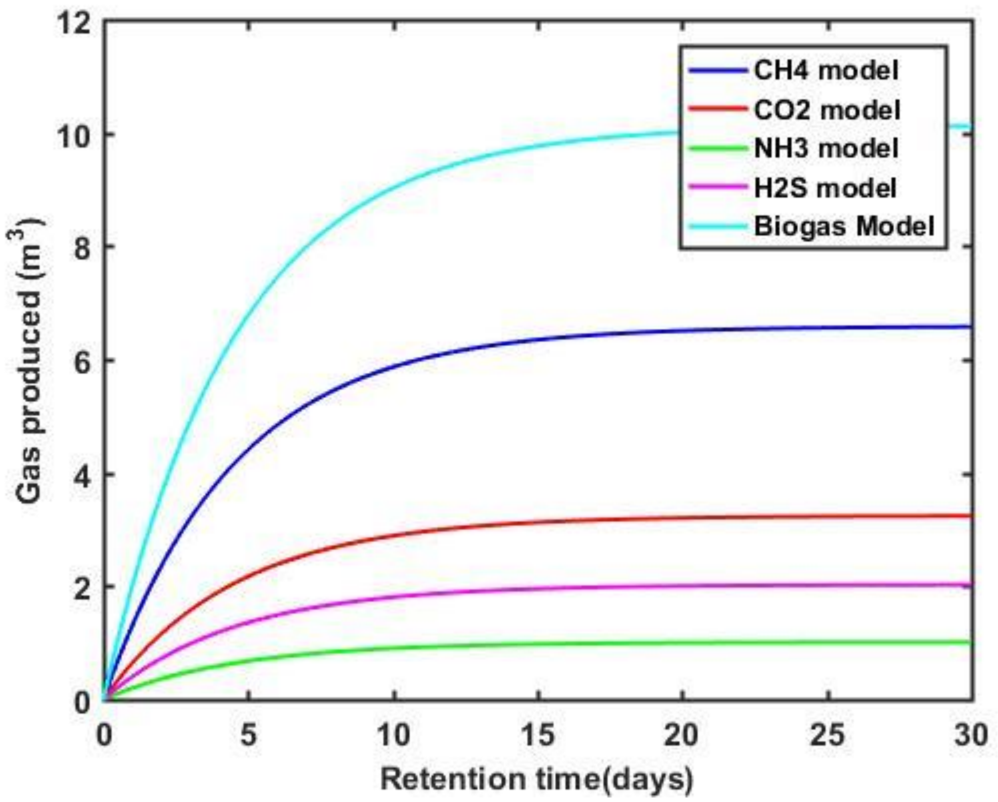


Figure 4. 1: Experimental model of the daily food waste 115 kg/day

Therefore, as shown on the above figure 4.1, it is possible to generate 10.35m^3 biogas from 115kg of food waste with in 30days. The biogas produces here consists of 6.18 m^3 of CH_4, 3.18m^3 CO_2, and 2m^3 of H_2S.

4.3. Digester design

An aerobic digester is a specially designed tank where the substrate is stored and fermentation takes place. And its scale can vary from a small household system to large commercial plants of several thousand cubic meters. As it is known digester is the core of a biogas system, and it should fulfill the following structural functions.

- Provide impermeability to gas and liquids
- Adequately pressure resistant
- Be durable or resistant to crack

Nowadays, there are many types of digesters available in the world [26]. Depending on dry matter content of the substrate, digester is usually classified into wet digestion and dry digestion. The former is fed with dry matter content lower than 15%, and is usually applied to solid animal manure, energy crops etc. while the latter between 20 and 40% and Wet it often involves manure and sewage sludge.

Concerning the construction, among different types of biogas plants the two most familiar types in developing countries are distinguished the **fixed-dome plants** and the **floating-drum plants**. Based on the following selection criteria fixed dome plant is preferred to be used for this research [27].

4.3.1. Fixed dome plants

Construct entirely below the ground saving space and being less affected by damage and daily temperature fluctuations. The gas is stored in the upper part of the digester. When gas production commences, the slurry is displaced into the compensating tank. Gas pressure increases with the volume of gas stored[44].

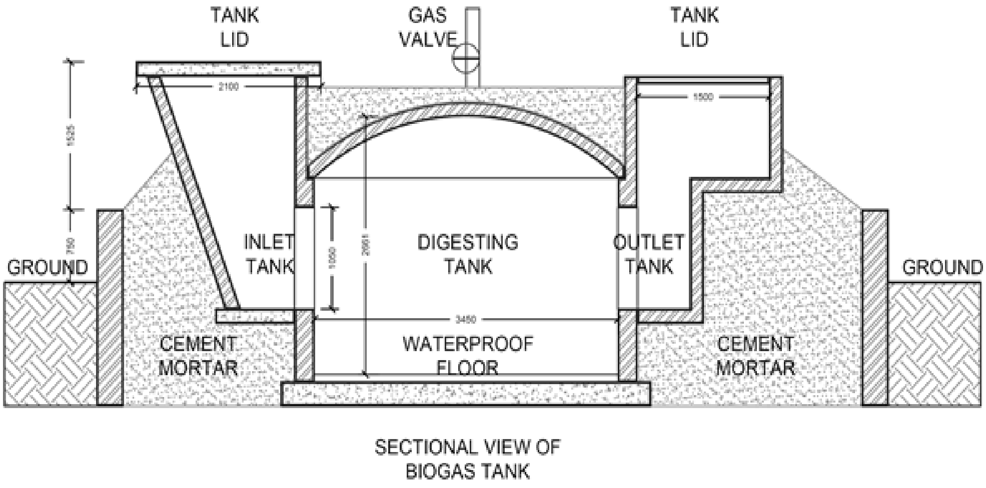


Figure 4. 2: Sectional view of fixed dome biogas digester [45].

4.3.2. Floating-drum plants

A floating drum plant consists of a cylindrical or dome shaped digester and a moving, floating gasholder or drums. The gasholder floats either directly in the fermenting slurry or in a separate water jacket. The drum in which the biogas collects has an internal and/or external guide frame that provides stability and keeps the drum upright. If biogas is produced, the drum moves up, if gas is consumed, the gasholder sinks back [46].

Figure 4. 3: Floating-drum plant type [45].

4.3.3. Sizing of digester

The biogas plant size is dependent on the average daily feed stock and expected hydraulic retention time of the material in the biogas system. Capacity of the plant should be designed 70 based on the availability of raw materials. Capacity of the plant indicates the quantity of gas produced in a day[39].

$$\text{Total volume of digester } V = V_C + V_{gs} + V_f + V_S\text{ ; Where,}$$

- Volume of gas collecting chamber = V_C
- Volume of gas storage chamber = V_{gs}
- Volume of fermentation chamber = V_f
- Volume of sludge layer = V_S

Volume of the digester can be calculated as follows:

$$V_C \leq 5\% \times V$$

$$V_S \leq 15\% \times V$$

$$V_{gs} + V_f = 80\% \times V$$

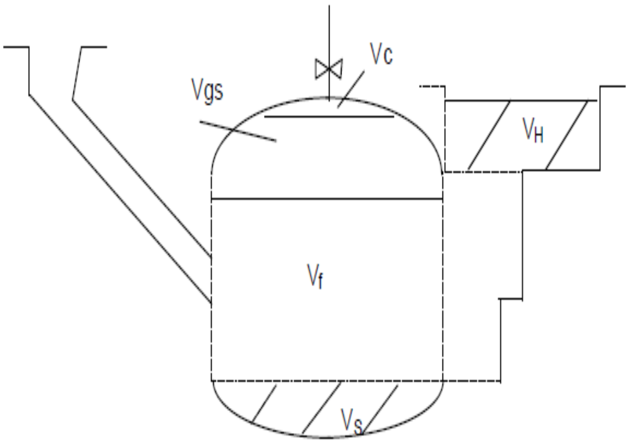


Figure 4. 4: Design of Biogas digester

$$\text{Working volume of digester } = V_{gs} + V_f$$

$$V_{gs} + V_f = Q \times RT$$

$$= 360\text{kg/day} \times 30\text{days}$$

$$= 10.200 \text{ Kg}$$

$$= 10.20m^3$$

Therefore, to produce the required amount of biogas 10m^3 fiberglass Roto tanker is used as a digester.

CHAPTER FIVE

5. CHEMICAL SCRUBBER DESIGN AND BIOMETHANE COMPRESSION

5.1. Introduction

Chemical scrubber works very similarly to the water scrubber method, but CO_2 does not solute physically only in water rather, it makes chemical reaction with scrubbing chemical it can be either NaOH or $Ca(OH)_2$. These results, the scrubbing process to work under very low pressure and low volume of fluid than water scrubber. Furthermore, it has high degree of purity, with minimum methane slip reported up to 0.01% [47].

Most of the time gas absorption is carried out in vertical counter current packed column. The liquid chemical solvent is fed at the top of the column and is distributed over the surface of the packing either by using nozzle shape injector or distribution plates. After CO_2 absorption processes the purified gas leaves the column at its top position of the scrubber.

The following assumptions are taken into account in developing and predicting result of the model for gas absorption packed column [48].

- ✓ Absorption process is carried out in a series of contacts, with the occurrence of counter-flow between the gas and diluted absorbent.
- ✓ The column operates at steady state conditions, hence heat has negligible effect in the absorption column
- ✓ There exists perfect mixing because of constant solute and solvent flow rates.

In order to design absorption column different parameters needs to be considered.

1. **Diameter:** Diameter of the column has to be wide enough to prevent flooding but at the same time as small as possible to limit the amount of liquid necessary to wet all the packing material for scrubbing.
2. **Height**: It depends on the necessity of contact time between the gas and liquid for optimal removal of CO_2 and remaining H_2S.
3. **Packing material:** Increases the surface area and contact time between the gas and the liquid.
4. **Flow rate**: It is a function of the raw gas flow rate and the liquid concentration. Controlling liquid flow rate are important for the maximum removal of CO_2.

The system need to have some predefined parameters.

5.1.1. Schematic diagram upgrading and stripping unit

The diagram displayed below shows the whole system, including stripping column and everything related to it. The parts needed for a full system are two columns (1 and 2). Column number one is an absorption column and column two for stripping column. Each column filled with suitable packing material (3 and 4). The absorption column usually filled with plastic pall rings, but the stripping column with heat and chemical resistant material.

At the bottom of the absorption column is a diffuser (5) to separate the gas coming from the gas inlet. Spray nozzles (6 and 8) are placed at the top of each column to ensure good dispersion of chemical solvent over the filling material. At the top of the absorption column, there is a mist eliminator (7) to remove any water vapor remain in the cleaned gas stream.

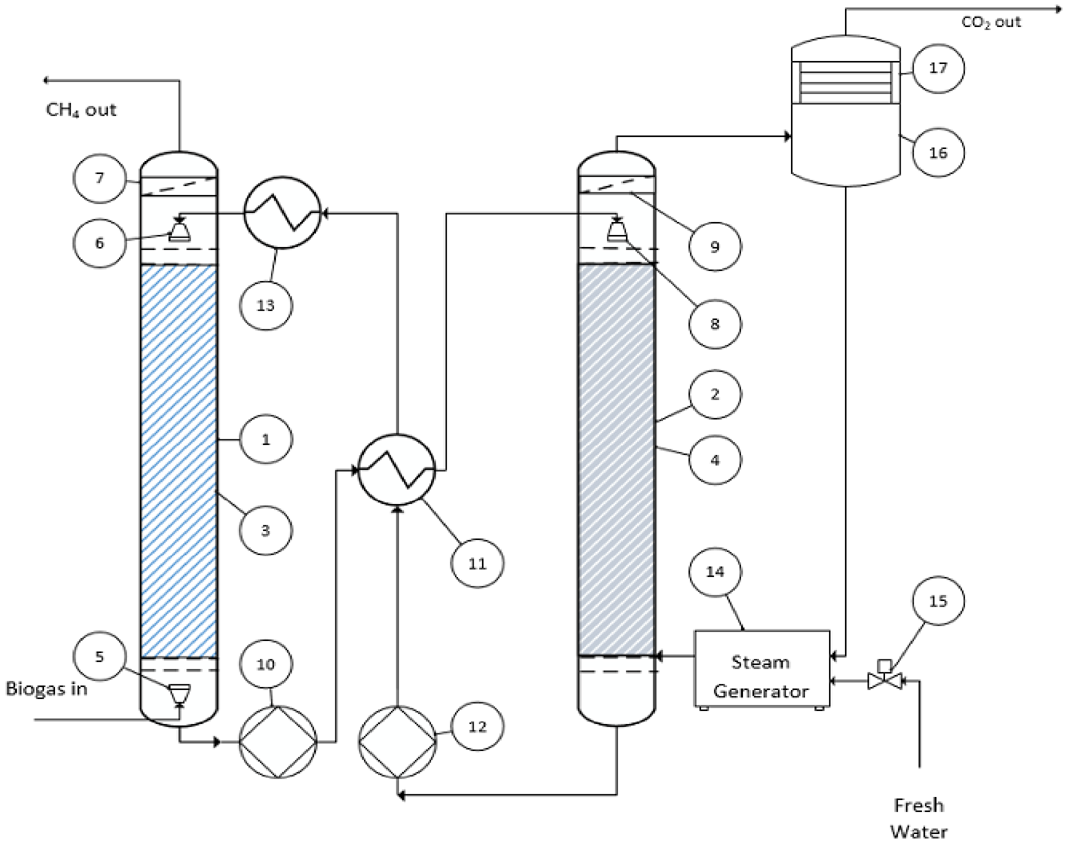


Figure 5. 1: Schematic diagram of chemical scrubbing technique

Two pumps (10 and 12) are needed. Their purpose is to pump saturated NaOH from the absorption column to the stripper and regenerate $Ca(OH)_2$ fluid from the bottom of the stripper to the absorption column.

In order to ensure good absorption, the $Ca(OH)_2$ solution needs to be cooled after the stripper. To do this a cooler (13) is placed before the $Ca(OH)_2$ solution enters the absorption column.

To strip the $Ca(OH)_2$ solution of CO_2 rich solution a steam generator is needed (14). The inlet of the steam is placed at the bottom at the stripping column. Into the steam generator, a solenoid valve (15) supplies the steam generator with additional water when needed. At the outlet of the stripping column, a flash tank (16) is placed in order to separate the CO_2 from the steam.

5.1.2. Packing material

The liquid load has an impact on CO_2 absorption efficiency, although it also varies from packing to packing, depending on geometric features. Choosing the right packing material is one of the key tasks to have very good absorption capabilities. The function of the packing material is to provide increased surface area of the column also increases the time gases inside the column are in contact with the liquid [49].

In addition, if the surface area of the packing material is too much wide it will also increase pressure drop along the column and thus increasing risk of flooding. The packing material is dependent on the liquids inside the column, and it is expected to be chemical, heat, and corrosion resistant.

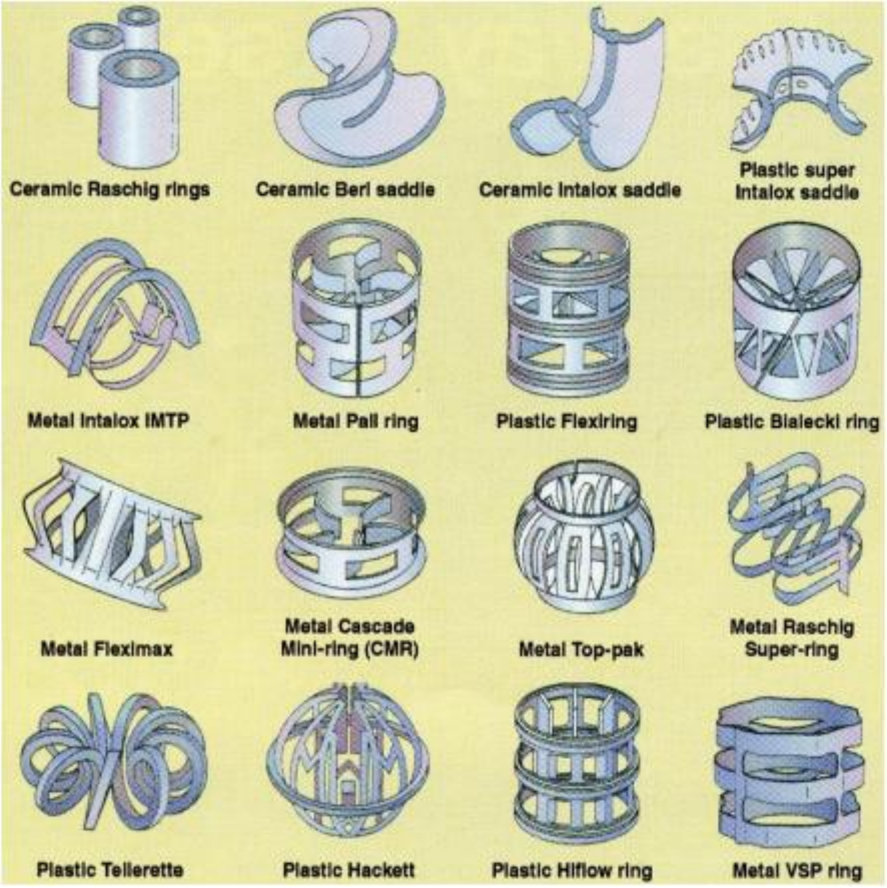


Figure 5. 2: Sample of different types of packing material [32]

Common materials are polyethylene plastic, ceramics, and stainless steel. All packing material has different properties. These properties are unique and are specified in datasheets provided from the manufacturer [15]. Based on, its resistance to corrosion while in contact with $Ca(OH)_2$ solution and its price PE plastic is a suitable choice to be used as packing material [17].

5.1.3. Column diameter

Using a generalized pressure drop-graph, by solving for F_{LV} and choosing an appropriate K_4 value, both are dimensionless. It is possible to determine the column diameter. The recommended pressure drop for absorption column is found to be 15 to 50 (mm water/meter of packed column height) [49]. Where K_4 and F_{LV} is a number, describing column and packing material properties and liquid and vapor flow rates respectively.

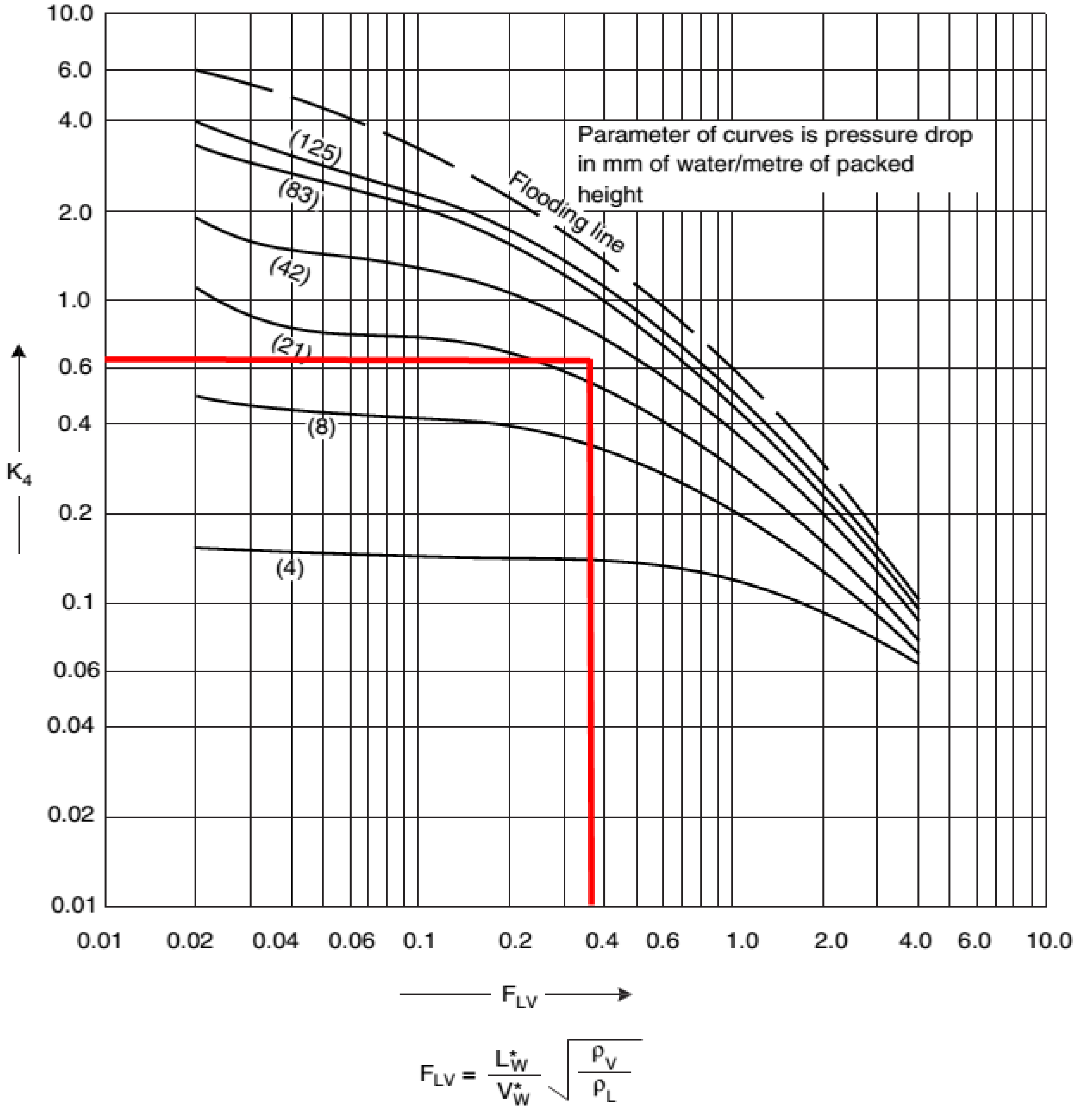


Figure 5. 3: Generalized pressure drop correlation adapted by Norton Co. [32].

- Determination of column diameter:

F_{LV} can be found using equation 25[49].

$$F_{LV} = \frac{L_{\dot{w}}}{V_{\dot{w}}} \times \sqrt{\frac{\rho_V}{\rho_L}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

Where, F_{LV} = is the liquid to vapor mas flow ratio (unit less)

$L_{\dot{w}}$ = is the liquid mass flow (kg/s)

$V_{\dot{w}}$ = is the vapor mass flow (kg/s)

ρ_L and ρ_V = are density of liquid and gaseous fluid (kg/m^3)

- Density liquid stream:

$$\rho_L = 0.1 \times \rho_{Ca(OH)_2} + 0.9 \times \rho_{H_2O} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

- Density gas stream:

$\rho_V = 0.30 \times \rho_{CO_2} + 0.65 \times \rho_{CH_4}$

- Total liquid stream and gas stream:

$L_{\dot{w}} = L_i \times \rho_L$………………………………………….………….. (5.3)

$V_{\dot{w}} = G_i \times \rho_V$……………………………...……...………………. (5.4)

$L_i = 0.033 \text{lit/sec}$; Where liquid mass flow rate in

$G_i = 1.44 \text{lit/sec}$; Where gas mass flow rate in

- Density liquid stream:

$\rho_{Ca(OH)_2} = 2210 \text{kg/m}^3$

$\rho_{H_2O} = 1{,}000 \text{kg/m}^3$

- Density gas stream:

$\rho_{CO_2} = 1.98 \text{kg/m}^3$

$\rho_{CH_4} = 0.66 \text{kg/m}^3$

K_4 is determined from F_{LV} value and the recommended pressure drop, which is between15 to 50 (mm water/meter of packed column height). Therefore, the selected K_4 factor was 0.62. This gives a pressure drop of approximately 38 (mm water/meter packed column) which is acceptable for such design.

After determining K_4 the diameter of the column can be found from V_m using equation 5.5 [49]

$$V_m = \sqrt{\left(\frac{K_4 \times \rho_V \times (\rho_L - \rho_V)}{13.1 \times Fp \times \left(\frac{\mu_L}{\rho_L}\right)^{0.1}}\right)} \text{……………………………………… (5.5)}$$

.Where, K_4 = is packing properties and liquid and vapor flow rates (unit less):

V_m = is gas mass flow rate over the cross section of the column [kg/m^{2}s]

F_p = is the packing material factor, see table 5-1.

μ_L = is the liquid viscosity [Ns/m^2]

ρ_L and ρ_V = are the liquid and vapor densities [kg/m^2]

$\mu_L = \mu_{Ca(OH)_2} = 1.03 \times 10^{-3} \text{Ns/m}^2$

$A = \frac{V_{\dot{w}}}{V_m}$……………………………………………….. (5.5)

$$d = \sqrt{\frac{A \times 4}{\pi}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.6)$$

Where, A = is the area of the column (m^2)

d = is the diameter of the column (mm)

The choice for packing material factor (F_p) has to be in regards to price, although with the table in mind, pall rings look promising for their big surface area [49]. The selected value of packing material factor is $F_p = 230$.

Item size(mm)	Packed density in (kg/m^3)	Surface area in (m^2/m^3)	Packing factor
16	112	341	230
25	88	210	160
38	76	128	92
51	68	102	66
89	64	66	52

Table 5. 1: Design data for various packing's [32].

Parameter	Value
ρ_L	$1121 \times 10^{-3} kg/L$
ρ_V	$1.023 \times 10^{-3} kg/L$
$L_{\dot{w}}$	$0.037 kg/sec$
$V_{\dot{w}}$	$0.0015 kg/sec$
F_{LV}	0.39
K_4	0.63
F_p	230
μ_L	$1.03 \times 10^{-3} Ns/m^2$
V_m	0.269kg/m^2s
A	0.0107m^2
D	0.110m

Table 5. 2: Result from scrubber column design.

From these calculations, the diameter was found to be 112 mm or 0.112m. A best choice of material for this paper would be a 110x2mm standard PVC pipe.

5.1.4. Column height

The height of the column is dependent on the contact time needed for full or acceptable absorption of CO_2. Most of the time, the height is usually determined by experience from similar equipment rather than mathematical conclusions[49]. This is done by comparing with other scrubbing design from literature. Here one project was taken where the gas flow found to be 7.6m^3/hr. The height of the column in this project was 2.3m [14]. Therefore, the size will be decided to be 1.6m for the gas flow of 5.20m^3/hr. This was done for two hours.

5.1.5. Thermodynamics

During absorption process, there is energy generation due to exothermic reaction between solute and solvent. Here maximum 50°C temperature will be attain due to heat generation while absorption process is takes place.

Therefore, by constructing the column out of PVC pipe the heat conduction keeps the column from excessive heating up. Based on heat transfer equation 31, It is possible determine amounts of heat generated inside the column [30].

$$Q = \frac{2\pi\lambda l}{ln\frac{D}{d}}(T_1 - T_2)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.7)$$

Where, λ = is the heat transfer coefficient,

l= is the length of the column,

D = is the external diameter of the column,

d = is the internal diameter and

T_1 and T_2 = is the internal temperature and external respectively.

The parameters for polyvinylchloride (PVC) pipe are as follows:

λ = 0.19 W/m °C and l = 2.4m

D=113mm and d=110mm

T_1=50°C and T_2=22°C

$$Q = \frac{2 \times \pi \times 2.2\text{m} \times 0.19\text{W/m℃}}{ln\frac{113m}{110m}} \times (50 - 22)\text{℃}$$

$$= 2.059kW$$

This means that the heat transfers through conduction from the inner to outer column become 2.059kW as shown in the figure 5.4.

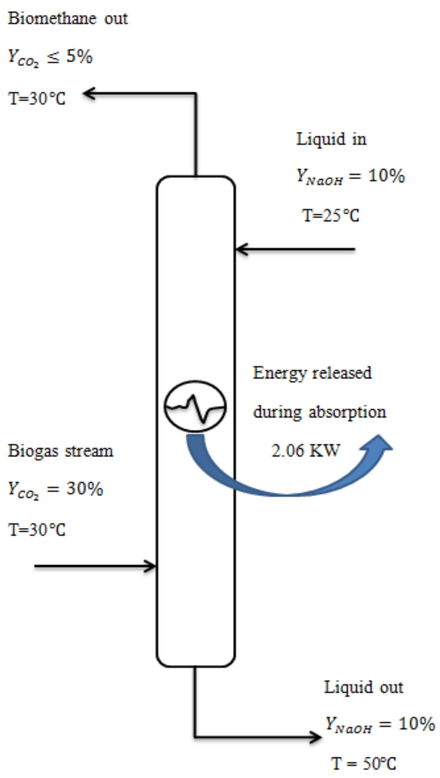


Figure 5. 4: Heat released from the absorption column by means of conduction.

5.2. Compressing and storing biomethane

Compressing and storing biomethane requires a gas compressor suitable for flammable gases. Compressing biomethane reduces the storage requirements, offers concentrated energy content and gives pressure to overcome the resistance to gas flow. Most commonly used biogas storage options are in propane or butane tanks and commercial gas cylinders up to 200bar. Depending on the application of biomethane the storage facilities will vary.

The biomethane gas compression and storage system consists of three units; a compressor, a pressure gauge and an LPG cylinder. The compressor used in the experiment is a hermetic reciprocating type compressor that is used for refrigerator and is commercially available. The pressure of the gas at various points of compression can be measured using a pressure gauge. In this case, a tyre tube was used as gas storage instead of LPG.

Moreover, compressing biomethane is important to eliminate the mismatch in pressure between fuel storage and electric generator to ensure efficient operation

5.2.1. Pressure Developed inside the Digester

According to Dalton's law, pressure of a gas mixture is equal to the sum of the pressure each gas would exert if it existed alone at the mixture temperature & volume [31].

$$\mathrm{P_m} = \sum_{\mathrm{i}}^{\mathrm{k}} \mathrm{P_i}(\mathrm{T_m}, \mathrm{V_m}) \ldots\ldots (5.8)$$

The partial pressure of a gas is the pressure exerted by a particular component of a mixture of gases [31].

$$P_i V_i = n_i R T \ldots\ldots (5.9)$$

Where, P_i = Pressure developed by each gas of mixture

V_i = Volume of particular component of gas

T = Temperature of mixture in Kelvin

R = Universal gas constant

n = number of moles of component

$\mathrm{V_{mix}}$ = volume of gas mixture

Here gas volume is constant throughout the system is $10.35m^3$ of biogas. According to their percentage composition, the volume of each gas in the mixture can be determined as follows.

The volume of constituent gas:

$$\mathrm{V_{CH_4}} = \%\ \text{Constituent gas} \times \mathrm{V_{mix}} \ldots\ldots (5.10)$$

$$\mathrm{V_{CH_4}} = \%\mathrm{CH_4} \times \mathrm{V_m} = 65\% \times 10.35\mathrm{m}^3 = 6.73\mathrm{m}^3/\mathrm{day}$$

$$\mathrm{V_{CO_2}} = \%\mathrm{CO_2} \times \mathrm{V_m} = 30\% \times 10.35\mathrm{m}^3 = 3.11\mathrm{m}^3/\mathrm{day}$$

$$\mathrm{V_{H_2S}} = \%\mathrm{H_2S} \times \mathrm{V_m} = 1.5\% \times 10.35\mathrm{m}^3 = 0.155\mathrm{m}^3/\mathrm{day}$$

The biogas saturates with water vapor and now the total pressure inside the digester is the sum of the dry gases and the water vapor pressures. By assuming the water vapor as an ideal gas, it is possible to determine volume and mass of moisture present in biogas using ideal gas equation.

Volume of water vapor present in biogas:

$$\mathrm{V_{H_2O}} = \%\mathrm{H_2O} \times \mathrm{V_m}$$

$$\mathrm{V_{H_2O}} = 4\% \times 10.35\mathrm{m}^3 = 0.414\mathrm{m}^3$$

Gas	**Molecular weight**	**Density kg/m^3**
Air	29	1.205
Ammonia (NH_3)	17.03	0.717
Carbon dioxide (CO_2)	44.01	1.842
Hydrogen sulfide (H_2S)	34.076	1.434
Methane (CH_4)	16.043	0.668
Water vapor (H_2O)	18.016	0.804

Table 5. 3: Densities and molecular weight and of selected compounds at STP

Density is given by:

$$\text{mass} = \text{Density} \times \text{volume} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (5.11)$$

Mass of constituent gas:

$$\text{mass} = \text{Molecular weight} \times \text{mole}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.12)$$

$$m_{CH_4} = 0.66\frac{kg}{m^3} \times 6.73m^3 \ = 4.44kg/day$$

$$m_{CO_2} = 1.98\frac{kg}{m^3} \times 3.11m^3 \ = 6.16kg\ /day$$

$$m_{H_2S} = 1.434\frac{kg}{m^3} \times 0.155m^3 \ = 0.222kg/day$$

Number of mole of constituent gas:

$$n_{CH_4} = \frac{m_{CH_4}}{M_{CH_4}} = \frac{4.44kg}{16.04\frac{kg}{Kmol}} = 0.277kmol/day$$

$$n_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{6.16kg}{44.01\frac{kg}{kmol}} = 0.139kmol/day$$

$$n_{H_2S} = \frac{m_{H_2S}}{M_{H_2S}} = \frac{0.222kg}{34.076\frac{kg}{mol}} = 0.0065kmol/day$$

The partial pressure of a methane gas:

$$P_{CH_4} = \frac{n_{CH_4} \times R \times T_m}{V_m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.13)$$

$$P_{CH_4} = \frac{0.277kmol \times 8.31kJ/molK \times 311K}{10.35m^3} = 69.17kPa$$

The partial pressure of a carbon dioxide gas:

$$P_{CO_2} = \frac{0.139Kmol \times 8.31KJ/molK \times 311K}{10.35m^3} = 34.71KPa$$

The partial pressure of a hydrogen sulphide gas:

$$P_{H_2S} = \frac{0.0065\text{kmol} \times 8.31\text{kJ/molK} \times 311\text{K}}{10.35\text{m}^3} = 1.62\text{kPa}$$

Partial pressure of saturated water at temperature 311K can be found from steam table[31].

$$P_{H_2O} = 6.6814\text{kPa}$$

Total pressured (P_T) developed in gasholder:

$$P_T = P_{CH_4} + P_{CO_2} + P_{H_2S} + P_{H_2O}$$

$$P_T = 69.17\text{kPa} + 34.71\text{kPa} + 1.62\text{kPa} + 6.68\text{kPa}$$

$$= 112.18\text{kPa}$$

5.2.2. Calculating compression ratio

r value	No. of Stages
1-3	Single stage
3-5	Single stage, occasionally two stage
5-7	Two stage, occasionally single stage
7-10	Two stage
10-15	Usually two stage, occasionally three stage
>15	Three stage

Table 5. 4: Compression ratio with respect to number of Stages[50].

$$P_d = P_s \times r \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.14)$$

P_S = Suction pressure

P_d = Discharge pressure

r = Compression ratio

$$P_s = P_T + P_a$$

P_a = atmospheric pressure = 1.025 bar

Whereas, the atmospharic pressure of Addis Ababa were taken during the suction pressure calculation

$$P_s = 1.1218\text{bar} + 1.025\text{bar} = 2.1468\text{bar}$$

$$P_d = 1.20\text{bar} + 1.025\text{bar} = 2.225\text{bar}$$

$$r = \frac{2.225\text{bar}}{2.1468\text{bar}} = 1.04$$

Therefore one stage compressor is suitable for the system of compression. The cost associated with compression is due to the increases in compression ratio.

The biogas produced from poultry manure is being dried, scrubbed, compressed, and stored at a pressure of 4bars in Belgium [15]. Across the system boundary volume of the gas after compression can be determined using can be determine simply using adiabatic compression process (that is Q = 0), the thermodynamic relation is given by:

$$\mathrm{P_1V_1^k = P_2V_2^k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (5.15)$$

$$\text{Where, } \mathrm{k} = {}^{\mathrm{C_p}}\!/\!_{\mathrm{C_V}}$$

$\mathrm{V_1}$ = Initial volume of biomethane that the plant produce per day.

$\mathrm{P_2}$ = Compressed raw biogas pressure (4 bar) [51]

$\mathrm{V_2}$ = Compressed volume

Substituting the values

$\mathrm{V_1} = 6.73\,\mathrm{m^3/day}$, $\mathrm{P_1} = 1.1218\, bar$, $\mathrm{P_2} = 4bar$ and $\mathrm{V_2} = ?$

For biomethane $\mathrm{k} = {}^{\mathrm{C_p}}\!/\!_{\mathrm{C_V}} = 1.3$

$$\mathrm{V_2} = \left(\frac{\mathrm{P_1V_1^k}}{\mathrm{P_2}}\right)^{1/\mathrm{k}} = \left(\frac{1.1218 \times 6.73^{1.3}}{4}\right)^{1/1.3} = 2.5\,\mathrm{m^3/day}$$

Compressed air temperature

$$\mathrm{T_2} = \mathrm{T_1}\left(\frac{\mathrm{P_2}}{\mathrm{P_1}}\right)^{\mathrm{k}-1/\mathrm{k}} = 311\left(\frac{4}{1.1218}\right)^{1.3-1/1.3} = 417.04\mathrm{K}$$

Power absorbed by biomethane

$$\mathrm{W} = \frac{\mathrm{k}}{k-1}\dot{m}R(\mathrm{T_2} - T_1) = 4.33 \times 0.00144 \times 0.707 \times (417.04 - 311) = 0.467kW$$

Motor power required

$$\mathrm{W}_m = \frac{\mathrm{W}}{\eta_c} = \frac{0.467kW}{0.85} = 0.55kW$$

Therefore, it is possible to compressed and store 2.5m^3 biomethane using 3m^{3}storage capacity pressure vessel (gas cylinder).

Total biogas compressed ($\mathrm{B_C}$) per year is:

$$\text{Total biogas compressed (BC)} = 2.5\,\mathrm{m^3/day} \times 365\mathrm{days/year}$$

$$= 924.67\,\mathrm{m^3/year}$$

According to Syed Zafar Ilyas (2006) he was able to compress 60m^3 of biogas in to 21.6m^3 using three stage compressor with 0.9kW power consumption[52].

5.3. Centrifugal pump

Pump is a steady flow device used to increase the pressure of a liquid. Centrifugal pump transfers energy to the fluid by accelerating the fluid on a circular path in the impeller. Then the inertia forces cause the chemical solution to be pumped in to CO_2 scrubber unit[53].

5.3.1. System head loss

To select the appropriate pump it needs to calculate the system head loss. Since water is incompressible fluid, there are no density changes during the flow.
The head loss in a pipe circuit falls into two categories;

1) Head loss due to viscous resistance (friction) extending throughout the total length of the circuit
2) b) Head loss due to localized affects such as valves, sudden changes in area of flow and bends. Here there is no sudden change because uniform cross sectional pipe is used.

a. Flow friction

Flow friction occurs in all the hydraulic components. At the wall, the fluid velocity is zero whereas it attains a maximum value at the pipe center. Due to these velocity differences across the pipe, seen in figure 5.5, the fluid molecules rub against each other. This transforms kinetic energy to heat energy, which can be considered as lost[53].

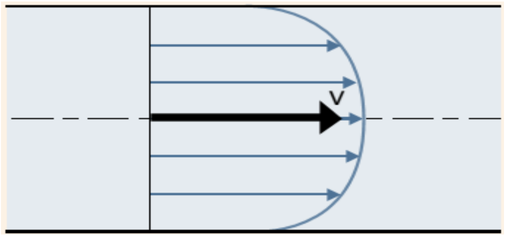


Figure 5. 5. Velocity profile inside circular pipe

The loss in the pipe depends on the fluid velocity, the hydraulic diameter of the pipe, length and inner surface roughness. The head loss due to friction in pipes may be obtained by using the Darcy-Weisbach’s equation.[54]

$$\mathrm{H_{Lf}} = \mathrm{f} \cdot \frac{\mathrm{LV^2}}{\mathrm{2gD}}$$

Where

$\mathrm{H_{Lf}} = \text{Head loss(m)}$

$\mathrm{f} = \text{friction coefficientn on surface of the pipe[dimensionless]}$

$\mathrm{V} = \text{Flow velocity into the component (m/s)}$

$\mathrm{L} = \text{Length of the pipe in (m)}$

$\mathrm{d} = \text{Diameter of pipe (m)}$

$\nu = \text{kinematic viscosity}$

The value of friction, for smooth pipes, may be obtained by using the following expression:

i. In laminar region, the flow is smooth and regular. The fluid layers do not mix macroscopically (more than a molecule at a time).[54]

   a) For laminar flow ($R_e < 2300$)

   $$f = \frac{64}{R_e}$$

ii. In turbulent flow, there is considerable mixing between layers. Most of the air and water flow in conduits will be turbulent. Turbulence leads to higher frictional losses leading to higher-pressure drop. For turbulent flow ($R_e > 2300$) [55].

$$f = \frac{0.3164}{R_e^{0.25}}$$

At p = 1.01325bar, and T = 313.15K kinematic viscosity of water equal to $0.478 \times 10^{-6}\, m^2/s$

Temperature ^{0}C	Density Kg/m^3	Kinematic viscosity v, m^2/s
0	1002	1.788×10^{-6}
20	1000	1.006×10^{-6}
40	995	0.657×10^{-6}
60	985	0.478×10^{-6}
80	974	0.364×10^{-6}
100	961	0.293×10^{-6}

Table 5. 5. Kinematic viscosity of water at different temperature

Scrubber solution flow rate (Q)

$$\dot{Q} = 2\mathrm{l/min} \;=\; 3.3 \times 10^{-5}\mathrm{m^3/s}$$

Diameter(D)of the hose or pipe; $D \;= 1\mathrm{cm} = 0.01\mathrm{m}$

$$V = \frac{\dot{Q}}{A} \qquad \text{where } A = \frac{\pi * D^2}{4}$$

$$A = 7.85 \times 10^{-5}\mathrm{m^2}\,, V = 0.42\mathrm{m/s} \text{ and } \nu \;=\; 0.657 \times 10^{-6}\,\mathrm{m^2/s}$$

Friction factor for pipe:

Then the Reynolds number will be determined using the formula given below:

$$R_e = \frac{0.42\mathrm{m/s} * 0.01\mathrm{m}}{0.\,657 \times 10^{-6}\,\mathrm{m^2/s}} = 6{,}398.5$$

$R_e > 2300$, implies turbulent flow

$$f = \frac{0.3164}{R_e^{0.25}} \;=\; \frac{0.3164}{(3{,}196.35\,)^{0.25}} = 0.035$$

$$H_{Lf} = 0.035 \times \frac{6\mathrm{m} \times (0.42\mathrm{m/s})^2}{2 \times 9.81\,\mathrm{m/s^2} \times (0.02\mathrm{m})} =\; 0.19\mathrm{m}$$

b. **Static head (m):** The static head H_{st} is the physical change in elevation between the sur face of the reservoir and the point of discharge into the receiving tank. Here the static head 1.1m.

c. **Head loss due to Bends**

The head loss due to a bend is given by expression.[54].

$$H_B \;= \frac{k_B V^2}{2g}$$

Where,

$H_B \;=$ minor loss due to bending of pipe

$K_B \;=$ coefficient which depends on the bend angle fittings.

$V \;=$ Velocity of water

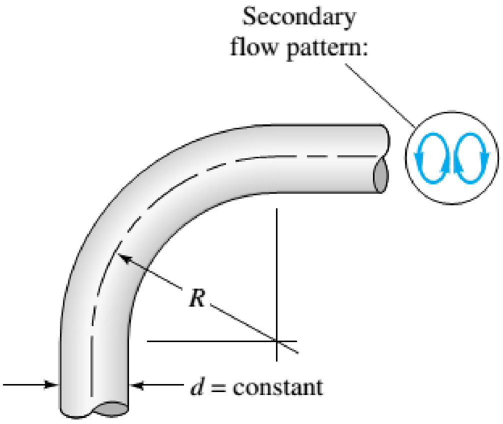


Figure 5. 6. Resistance coefficients for 90° bends elbows

For elbow connection and considering the average number elbow 4.

$K_B \ = \ 0.5$

$$H_B \ = \frac{0.5 * (0.42m/s)^2 \times 4}{2 * 9.81\, m/s^2} = 0.017m$$

d. Head loss due to Valves

The head loss due to a valve is given by expression

$$\mathrm{H_V} \ = \frac{\mathrm{k_V V^2}}{\mathrm{2g}}$$

$\mathrm{H_V}$ = minor loss due to valves

$\mathrm{K_V}$ = Loss coefficient depends upon the type of valve and degrees of opening

V = Velocity of water

Valve type	K_V
Globe valve, fully open	10
Gate valve, fully open	0.2
Gate valve, half open	5.6

Table 5. 6. Typical valves of loss coefficients for gate and globe valves

For gage valve half open $\mathrm{K_V}$ =5.6 and number of valves = 4

$$\mathrm{H_V} \ = \frac{5.6 \times (0.42)^2}{2 \times 9.81 m/s^2} = 0.05m$$

e. **Dynamic head:** The dynamic head is generated as a result of in the square of the velocity within the system.

$$\mathrm{H_{dyn}} = \frac{\mathrm{V^2}}{\mathrm{2g}} = \frac{(0.42\mathrm{m/s})^2}{2 \times 9.81\mathrm{m/s^2}} = 0.01\mathrm{m}$$

Total head loss: The overall head loss is a combination of both the above categories.

$$\mathrm{H_{TL}} = \mathrm{H_f} + \mathrm{H_{st}} + \mathrm{H_B} + \mathrm{H_V} + \mathrm{H_{dyn}}$$

$$\mathrm{H_{TL}} = 0.19\mathrm{m} + 1.1\mathrm{m} + 0.017\mathrm{m} + 0.05\mathrm{m} + 0.01\mathrm{m} = 1.367\mathrm{m}$$

The power requirement for the pump with efficiency of 85% can be calculated by:

$$\mathrm{P(kW)} = \frac{\mathrm{Q \times \rho \times g \times H_{TL}}}{\eta_{\mathrm{pump}}}$$

$\rho_{\mathrm{L}} = 0.1 \times \rho_{\mathrm{Ca(OH)_2}} + 0.9 \times \rho_{\mathrm{H_2O}}$ where $\rho_{\mathrm{L}} = 1121\mathrm{kg/m^3}$

$$\mathrm{P(kW)} = \frac{3.3 \times 10^{-5}\mathrm{m^3/s} \times 1121\mathrm{kg/m^3} \times 9.81\mathrm{m/s} \times 1.367\mathrm{m}}{85\%} = 0.58\mathrm{kW}$$

5.3.2. Pump selection

A pump has been selected from manufacturer's details that can achieve the required flow. Having determined the size of the columns and the liquid flow rate, the pumps necessary for the project can be selected from supplier catalog. The pumps need to withstand volatile liquids and have a hundred percent duty cycle, since they are predicted to operate constantly. Therefore to over come the head loss the 0.6kW out put power centrifugal pump is required.

MODEL	Total head in (m)	Power Rating (kW)	Power Rating (HP)	Discharge in (lit/min)
HL37	1.4m	0.6	0.8	2

Table 5. 7: Centrifugal pump selection supplier catalog

CHAPTER SIX

6. ELECTRICITY GENERATION

6.1. Introduction

Electric energy consumption per capita in the world is increasing. The satisfaction of increasing demand for energy requires higher consumption of fossil fuels, which is exhaustible and responsible for greenhouse effect. This leads to search for renewable sources of energy, to increase energy production efficiency as well as CO_2 capture[10].

Biomethane can be converted into electric power through several methods. It can be used alone with 100% biomethane generator, it is also possible to generate electricity from biomethane using duel fuel generator it might be either gasoline or diesel generator. In addition, it is possible to utilize it as a fuel for steam power plant to heat water in the boiler but it requires huge capital investment[34].

To select the appropriate power generation technology, the following basic requirement should be met and is putted as comparison criterion. This are:

- ✓ Availability on current market
- ✓ Investment cost to install
- ✓ Simplicity during modification

6.1.1. Hundred percent (100%) biogas generator

An electric generator, which is utilizes 100% biofuel, is known by gas engines. Both compression and spark ignition can be employed by this technology. Carburetor is replaced by venturi system to introduce gas into the air flow. Using biomethane it is possible to generate maximum power output, reduce corrosion in mechanical parts and possible to increase fuel efficiency. However, the problem exist here is it is not well established yet in Ethiopian market. Therefore, it is difficult to choose it for our case [35].

6.1.2. Genset (Engine - generator set)

It is a combination of an electrical generator and vehicle engine as prime mover mounted together as a single piece of self-contained equipment. It is safe to install even on the domestic level, ranging from small to very large size [56].

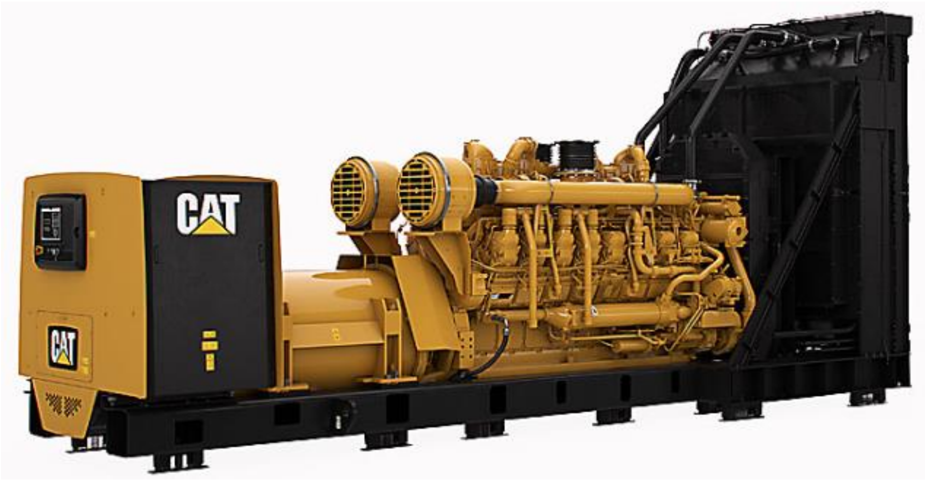


Figure 6. 1: Genset (Engine - generator set) generator for electricity generation

An electric generator was connected with an engine (Honda modeled GX 160) modified for use with biogas fuelling. At the operated speed of 3000 rpm, the engine was designed to generate electricity at 220 V, 50 Hz and 2.2 kW with gasoline fuelling [57]. However, it is very expensive as it is compared with dual fuel generator and requires highly skilled labor. Therefore, due to this reason it not preferable for this task.

6.1.3. Combined heat and power (CHP)

An integrated energy system that can be modified based on the energy need. CHP is a decentralized power generation technology that guarantees advanced energy efficiency. It uses single fuel to produce both heat and electricity. CHP is an all in one that powerfully converts up to 90% of valuable energy into electric and thermal energy (40% for electrical and 50% thermal) [35]. Low performance CHP systems have poor electrical efficiency up to 28% this unit bleed out huge costs and emit larger volume CO_2. Can provide integrated systems for cooking, heating and electric power.

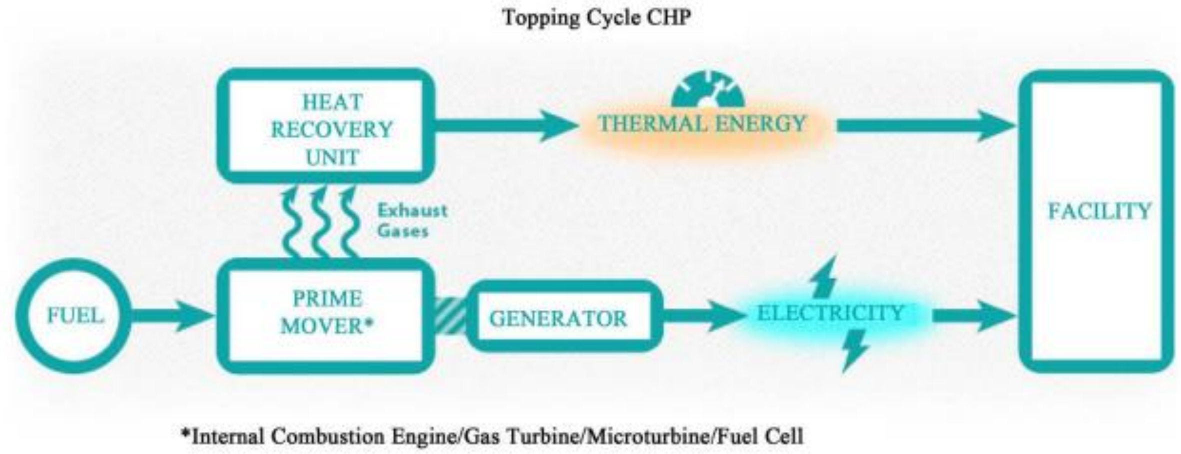


Figure 6. 2: operating system of Combined heat and power (CHP) [58].

6.1.4. Dual fuel

Dual-Fuel engines are engines modified to operate simultaneously on two fuels. Power generation through dual-fuel generator is also called as ‘Flexible-fuel engine. The dual fuel generator engine sucks and compresses a mixture of air and biomethane fuel, which has been prepared in external mixing device [12].

A dual fuel diesel engine generator in which the combustion process starts when the air-fuel mixture self-ignites due to high temperature and diesel fuel sprayed in the combustion chamber caused by high compression. The amount of diesel fuel needed for sufficient ignition is between 10% and 20% of the amount needed for operation on diesel fuel alone [59].

According to tippayawong, a small diesel engine with biogas and diesel mixed fuel to assess its endurance over the course of 2,000 hr. The results showed that it had 7% higher power output and superior efficiency compared to normal diesel engines[34].

In case of gasoline generator, it is possible to operate spark ignition (Otto system) by using only biomethane fuel. The engine is designed to operate on an air/fuel mixture with spark ignition. Sometimes in practice, a little amount of petrol (gasoline) fuel is added to start the engine. Here the amount of gasoline fuel needed for sufficient ignition is found in the range of 5% to 10%. Normally this technology will be used for very small generator sets (0.5-10 kW) as well as for large power plants[25].

According to Shenzhen Kingway brewery spark ignition engine of biogas fueled without removal of CO_2, generate electricity 246kW with efficiency of 28.45%, discharged heat of 99kW by engine exhaust and of 66kW by water jacket for cooling, dispersed heat of 2.8kW by convection and of 4.6kW by radiation [60].

A. Modification of a diesel engine generator into a biomethane generator

This modification involves a major operation on the engine generator and the availability of certain parts, which have to be changed. These alterations are:

- Removal of the injector pump and injector nozzles
- Mounting of an ignition system with, ignition coil, spark plugs and electric supply (alternator)
- Provision of a mixing device for the supply of an air/fuel mixture with constant air/fuel ratio (Venturi mixer or pneumatic control valve)[25].

B. Modification of gasoline electric generator

Here the basic modification is the provision of an air/gas mixer instead of carburetor [59]. Valve is installed to control the flow of the purified biogas. Then the mixture of biomethane and air enter in to the combustion chamber. It should be noted that during starting the generator, the flow rate of the biomethane recommended to be maximum until the generator start running smoothly [59].

So that in the case of petrol engine the modification is seemed to be easy as compared to diesel engine generator. During modification, it requires simple replacement on carburetor either by venturi mixer or T-joint tube-type mixer only where as in the case of diesel generator; it is more complex and more costly.

C. Venturi Mixer

A venturi mixer utilizes the same fluid-mechanic effect as a standard carburetor. The change in airflow quantity and velocity causes a change in pressure at the channel contraction. The need to supply the engine cylinders with a well-defined mixture under all circumstances has become more essential for better engine performance.

Need for venturi design

- The need to supply the engine cylinders with a well-defined and appropriate A/F mixture
- The conventional carburetors, as per as use for biogas engine are not appropriate because, it is designed for liquid fuels like gasoline.

- Biogas, as a gaseous fuel, requires the intake device only for mixing the fuel with air properly and acceleration and deceleration of engine.

Here venturi type of biogas mixer was analytically design of the intake device without major modification. The alteration in the intake device is much simpler and cheaper compared to that of modifications on combustion chamber. simple modifications on the carburetor venturi and these modifications would not create complications in the carburetor system[61].

The pressurized flow will increase volume of the fuel, hence improve the volumetric efficiency and the turbulence will increase the homogeneity of mixture, hence improve the flame speed [62].

Figure 6. 3. Modified carburetor[62]

The engine's power and speed control is performed by a variation of the supply of the air/fuel mixture to the engine. This is achieved by the operation of a butterfly valve situated between the actual mixing device and the engine inlet.

The venturi principle functions as follows:

For high air volume flow[63]:

- ✓ Air velocity is high.
- ✓ Air pressure is low at the contracted cross-section.
- ✓ The pressure difference between fuel gas and airstream is high.
- ✓ Much fuel gas flows through the openings to mix with the airstream.

For low air volume flow:

- Air velocity is low.
- Air pressure is high at the contracted cross-section.

- The pressure difference between fuel gas and airstream is low.
- Little fuel gas flows through the openings to join the airstream

Procedure during dimensioning a self-made venturi mixer for 4-stroke engine:

Step 1: Determine the volumetric intake V_{air}, (in m³/s) of the engine as a function of engine cubic capacity V_i (in m^3/s) at rated or maximum operational engine speed n (in 1/min or rpm) using equation 6.1[63].

$$V_{air} = \frac{V_i \times n \times \eta_{vol}}{2000 \times 60} \quad \text{(6.1)}$$

V_{air} = Volumetric air intake

V_i = engine cubic capacity

n = engine speed

η_{vol} = Volumetric efficiency

Step 2: Cross-sectional area of intake (and tube mixer), A_i:

$$A_i = \frac{\pi \times d^2}{4}$$

d = manifold diameter

Step 3: Intake velocity, C_i [64]:

$$C_{air} = \frac{V_{air}}{A_i} \quad \text{(6.2)}$$

Step 4: Volume flow of biogas (fuel consumption, fc) at rated power:

$f_c = sfc \times P$

f_c = fuel consumption

sfc = specific fuel consumption

P = rated power

Step 5: Cross-sectional area A_n and diameter d_n of nozzle: where velocity at gas nozzle is $C_n = 20 m/s$ [63].

$$C_n = \frac{f_c}{A_i} \quad \text{(6.3)}$$

$$d_n = \sqrt{\frac{4 \times A_n}{\pi}}$$

Parameter	**Value**
V_i	420cc
n	3600 rpm
η_{vol}	85%
V_{air}	$0.0107m^3/s$
d	60mm
A_i	0.0028
C_{air}	3.82m/s
f_c	$0.0019m^3/s$
A_n	$0.0001m^2$
d_n	11mm
ρ_g	$1.023kg/m^3$
ρ_g	$1.26kg/m^3$
P_a	1.01325kP
P_n	0.789kP
V_g	$90m/s$
m_g	0.01kg
m_{air}	0.15kg

Table 6. 1. Venturi meter design parameters and values

Step 6: The area at the venturi bottleneck is found using the continuous flow equation[53]. The velocity at the bottleneck ranges between C_v= 100 ... 150 m/s. A smaller bottleneck diameter increases the venturi velocity while a larger one decreases it respectively [63]. The venturi bottleneck area is can be determined using $C_v = 150$ m/s.

$$C_v \times A_V = C_{air} \times A_i$$

The gas nozzle diameter of 11.27mm can thus be assumed to be sufficient for operation under the conditions specified. Venturi bottleneck area and diameter are $7.13 \times 10^{-5} m^2$ and 8mm. According to Ni Ketut Lasmi (2016) design for 100cc the inlet diameter is 5mm and 3.5mm outlet diameter [62].

Step 7: Calculate pressure at throat

$$P_n = P_{air} + \frac{\rho_{air}}{2}({C_{air}}^2 - {C_n}^2)$$

Step 8: Calculate the velocity of gas at throat

$$V_g = K_v \times \frac{\rho_g}{2}(P_g - P_n)$$

K_v =Velocity Coefficient; where K_v =0.8 for small holes

Step 9: Determine the mass of biogas fuel flow.

$$m_{air} = \rho_{air} \times V_{air}$$

Step 10: Calculation of mass of biogas (m_{gas})

$$Air/gas\ ratio = \frac{m_{air}}{m_{gas}}$$

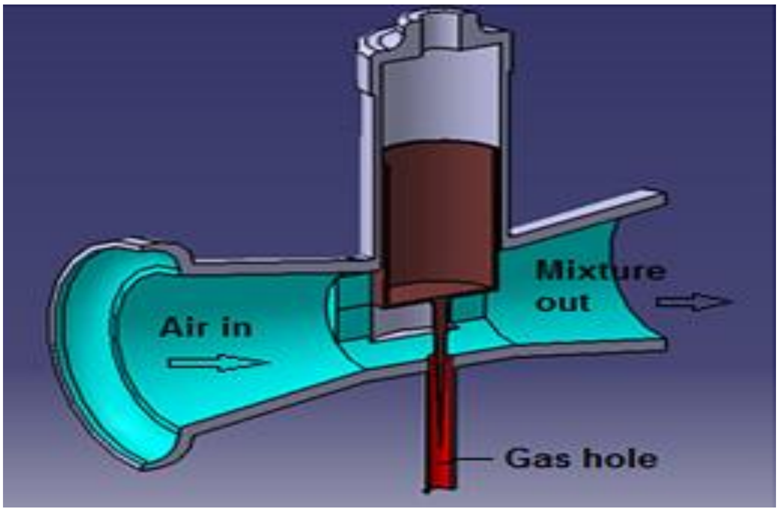


Figure 6. 4. Venturi meter Catia Model

A hole will have to be drilled into the carburetor body at a suitable place to insert the biogas supply pipe in such a way that it meets the internal ring channel of the venturi ring. The biogas supply pipe or a short tube for connection to a flexible hose pipe will have to be threaded if the carburetor body's wall thickness allows for screwing in. Otherwise, a two-component epoxy resin glue can serve the purpose[63].

In addition, gasoline fueled single cylinder generator engine are well established and available in Ethiopia market with reasonable price [33]. The maximum RPM (revolution per minutes) that can be obtained by using 100% biomethane was found about 1800 rpm. When the LPG is added to from 10% (90% biogas) to 20% LPG mixture then the engine speed was found to be increase from 2600 rpm to 3600rpm [59].

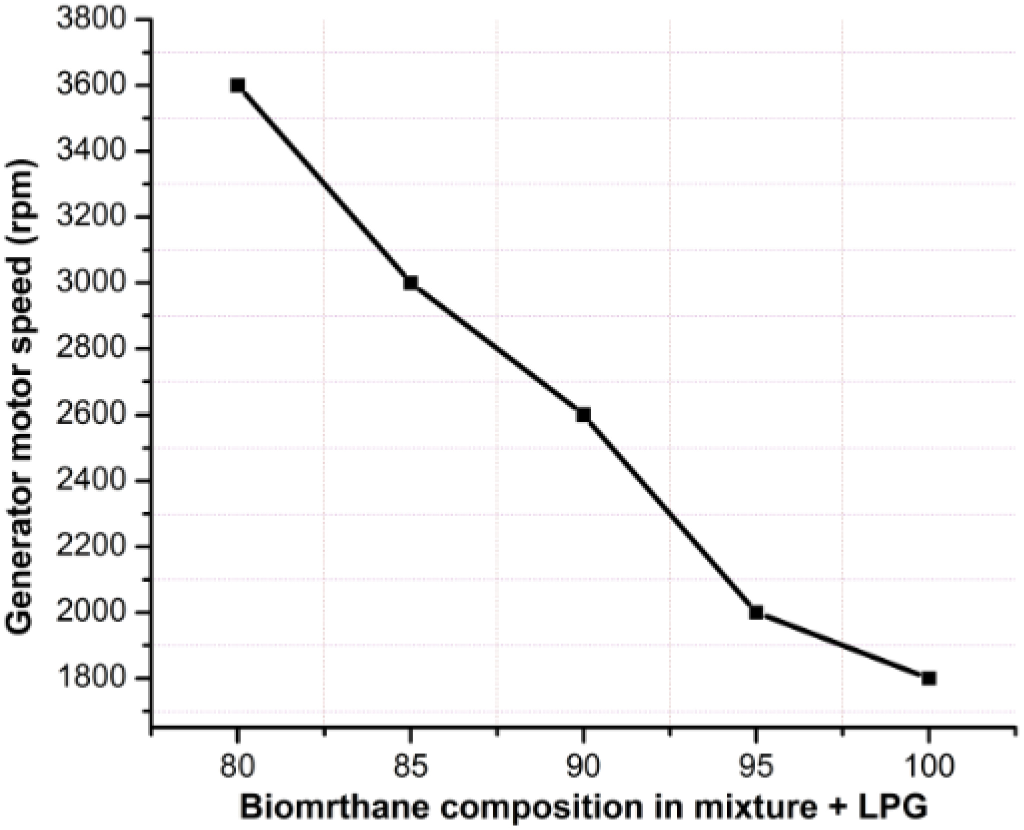


Figure 6. 5: Effect of biomethane and LPG mixture on speed of the generator engine

6.2. Combustion process inside generator engine

Air-fuel ratio AF is usually expressed on a basis of mass and is defined as the ratio of the mass of air to the mass of fuel during a combustion process of fuel [31].

A. Actual chemical equation of biomethane:

For 5% Oxygen in the exhaust, % O_2= 0.05 and X = 1.99

Balanced chemical combustion reaction equation of biomethane is shown as follows [34].

$(0.86\ CH_4 + 0.14\ CO_2 + 0.01\ N_2) + 1.87(O_2 + 3.76\ N_2) \rightarrow CO_2 + 1.88H_2O + 0.05O_2 + 7.02\ N_2$

$$AF_{actual} = \frac{(\text{mole of air} \times \text{Molar mass of air})}{(\text{mole of methane} \times \text{Molar mass of methane})}$$

$$AF_{act} = \frac{(1.87\text{mol} \times 32\text{kg/mol}) + (1.87 \times 3.76\text{mol} \times 28\text{kg/mol})}{(0.90\text{mol} \times 16\text{kg/mol}\ ) + (0.04\text{mol} \times 44) + (0.01 \times 28)}$$

$$= 15.62 \text{ kg of air/kg of biomethane}$$

Therefore, 15.62Kg of air is required to combust 1kg of biomethane fuel.

6.3. Electricity Generation using biomethane fuel

Here 115Kg of SFW are available to generate 10.35m^3 biogas within each day. Then using chemical upgrading technology it is possible to produce 6.17m^3 biomethane with 90% methane content in each day. According to literature review calorific value of biomethane with methane concentration for more than 85 % reach 45 to 55MJ/m^3 [9][65].

Based on the current electricity problem exists in Addis Ababa, in average the generator expected to work for nine hours per day with a fuel consumption calculated as follow;

$$\text{fuel consumption} = \text{biomethane/day} \times 1/9\text{hour} \times 1\text{day}$$
$$= 10.35\text{m}^3/\text{day} \times 1/9\text{hour} \times 1\text{day}$$
$$= 1.15\text{m}^3/\text{hour}$$

Amounts of electric power generated:

$$\text{Power available} = 1.15\text{m}^3/\text{hour} \times 1/3600\ \text{sec/hour} \times 50\times10^6\text{J/m}^3$$
$$= 15.97\ \text{kW}$$

The biomethane conversion efficiency of the selected generator is 38%. Then the rated electric power generated in each day can be calculated as follow:

$$\text{Electricity production from biomethane} = 0.38 \times 15.97\text{kW}$$
$$= 6.07\text{kW} \cong 6.1\text{kW}$$

Therefore, to solve such problem the generator expected to work for maximum 9 hours per day with rated power 6kW by consuming 1.15m^{3}biomethane per hour.

$$\text{Electricity production from biomethane per day} = 6.1\text{kW} \times 9\ \text{Hour/day}$$
$$= 54.9\text{kWh/day}$$

Electricity production from biomethane per year:

$$\text{Electricity production per year} = 54.9\text{kWh/day} \times 365\text{days} = 20.04\text{MWh/year}$$

6.3.1. Generator engine efficiency

Internal combustion engine does not convert all the energy, which is chemically available in fuel in to mechanical work, and some of the added energy is dissipate in the form of heat. This means that an engine's efficiency is less than 100%.

The heat generated during combustion heats up the cylinder walls. Part of the thermal energy radiated and lost. Up to 20% of heats generated inside the combustion chamber will loss due to thermal loss. And up to 21% of heat produced from the available biofuel is lost due to exhaust gas emission this is either as a result of incomplete combustion or energy lost due to presence of nitrogen gas which absorb much amounts of energy produced during combustion of A/F mixture.

In addition, high amount of energy produced during combustion reaction become lost because of cooling system. For air-cooled generator due to convective heat transfer 15% of heat lost to the surrounding air, because of the temperature gradient exists between the combustion chamber and the surrounding air. Finally, 6 % of heat will be lost because of total friction exists between moving parts in the engine itself and auxiliary equipment. For instance, due to the piston ring friction at the cylinder wall and the bearing friction.

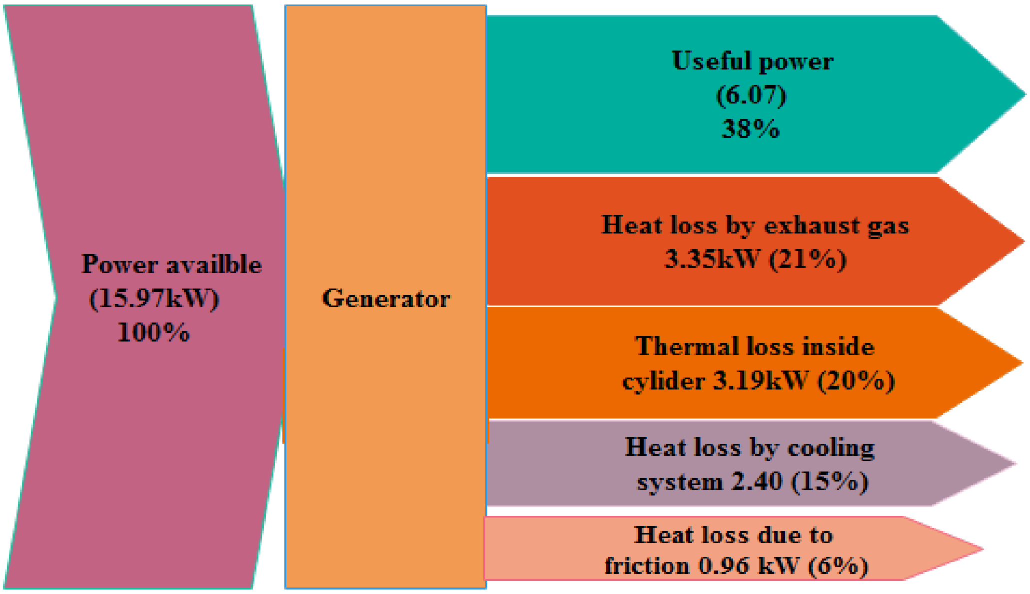


Figure 6. 6: Energy balance in internal combustion engine generator

6.3.2. Generator sizing

The first thing that we will need to do is determine what type of load that the customer will be using with the generator. It is to size generator using resistive loading.

Resistive, or reactive, loads are devices that use a heating element and require the same amount of power to start as to run. Examples include light bulbs and appliances such as heaters, toasters, irons and skillets. Next, ask your customer to provide you with the voltage, amperage, and wattage of the tools that will be run off the generator. With this information, you can easily determine the total wattage requirement of the equipment being used. This is accomplished by using the power formula [66].

The following table gives some information on the average wattage utilized by some commonly used appliances:

No.	**Appliance**	**Average wattage**
1	Refrigerator/Freezer	500-800
2	Light Bulb	100-500
3	Water Heater	3,000-3,400
4	Television	300-400
5	Window Fan	200
6	Computer	400
7	Fax Machine	90
8	Copier	200

Table 6. 2: Table average wattage used by some common appliances[66]

A. **Generator motor Speed (n):-** The motor speed describes the number of total (360°) revolutions of the crankshaft in a certain period, usually per one minute, i.e. 1/min or rpm. From the figure 6.10, it is possible to understand that for 100% biomethane fuel the rpm of gasoline generator became 1800rpm and it is also possible to produce 3600rpm by blending biomethane with petrol engine to generate 6kW power.
B. **Torque:** Torque is the actual twisting force an engine can produce via converting the piston's reciprocal movement in to the crankshaft rotational movement. The piston up and down movement due to the expanding force of A/F mixture is converted into rotational motion of crankshaft. The action of the engine serves as a prim-mover for generator motor [66].

$$\text{Torque (Nm)} = \text{Force (N)} \times \text{ Generator motor speed (rpm)} \ldots\ldots\ldots\ldots\ldots\ldots \text{(6.4)}$$

C. **Power, (P):** There is a wide range of engine-driven generators available, from portable units capable of supplying a few hundred watts of power to enormous, multi-megawatt units capable of supplying grid power for a small city. Since an engine transforms biochemical energy into mechanical energy through the combustion of fuel, the action of generator motor also transform the mechanical energy in to electrical power [66].

$$\text{P(kW)} = \text{Torque(kJ)} \times \text{Generator motor speed(rpm)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6.5)}$$

A generator converts mechanical energy into electrical energy. Electricity is commonly described in terms of voltage, Current and power.

D. **Voltage (V):** Voltage is the force that causes electricity to flow through wires, while current is the movement of electricity.

E. **Current (I):** Direct Current (DC) is an electrical charge that flows in one direction through a circuit. It is commonly used in consumer goods such as radios and automobiles [66].

$$\text{Power (kW)} = \text{V} \times \text{ I} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.6)$$

$$\text{V} = \text{Voltage(V)}$$

$$\text{I} = \text{Current (A)}$$

$$\text{I} = \frac{6\text{kW}}{220\text{V}} = 27\text{A}$$

F. **Frequency:** The rate at which alternating current changes direction determines its frequency. Each time the current goes one way and then the other way is called a cycle. Frequency is the number of cycles that occur in a single period. Frequency is also commonly referred to as Hertz (Hz). In the United States, standard household frequency is 60 Hz while many other countries use 50 Hz current [66].

$$\text{N} = \frac{\text{Z} \times 120}{\text{n}}$$

$$\text{n} = \text{generator motor speed}$$

$$\text{N} = \text{number of pole}$$

$$\text{N} = \frac{50\text{Hz} \times 120}{3600 \text{ rpm}} = 1.67 \cong 2$$

Therefore, the generator motor decided to be 2-pole generator with 27A.

G. **Phase:** Phase is a term applied to designate the circuits of an AC system. In the single-phase system, the voltages are in the same time phase in all parts of the system. In the three-phase system, the voltages are 120° apart.

Model No.	**GAC6HZR**
Types of fuel	Gasoline generator
Output Power	6kW
Number of stroke	4-Stroke
Output Type	AC Single Phase
Starting:	Hand Start/Recoil / Electric
Phase	Single-Phase
Displacement	420cc
Frequency:	50/60Hz
Specification	605×445×445mm3
No. Pole	2 pole
Rated voltage	220-240V
D & L- Bore & stroke of engine	0.06m & .059m resp.

Table 6. 3: Specification for selected gasoline generator

CHAPTER SEVEN

7. RESULT AND DISCUSSION

The experimental evaluation of biogas upgrading using aqueous solution of NaOH and $Ca(OH)_2$ is done to compare and select the appropriate CO_2 absorber. After purification chemical analysis was performed using portable gas analyzer to measure degree of purity of the gas. Finally, purified gas (biomethane) compressed, stored, and supplied to gasoline generator with the objective of electricity generation.

7.1. Experiment result

In this study the parameters such as time, and initial and final concentration of CO_2, H_2S, and H_2O in the gas stream is analyzed. Contact time, is an important factor that determine degree of purity of the gas. The experiment was conducted several times with time span of two hours and data was taken within 20 minute. The experimental tests performed led to the following results.

7.1.1. Removal of CO_2 by absorption tests in an aqueous solution of NaOH

Aqueous solutions of $Ca(OH)_2$ and NaOH are used independently during the experiment and they have their own CO_2 absorption efficiency. As CO_2 is an acidic gas, it reacts with $Ca(OH)_2$ solution produces a white precipitate of sodium carbonate (Ca CO_3) upon dissolving in water. When raw gas and absorbent chemical meet inside scrubber column physical absorption as well as chemical reaction will be takes place.

Then within 20min the liquid solvents react rapidly and high proportion of CO_2 being absorbed. As a result, concentration of CO_2 becomes decrease almost sharply. However, as the absorption process proceeded with time, the CO_2 was continuously accumulated in the solvent solution and it remained stable between 60 to120 min. The end of each run then determined when the liquid solvent became saturated.

Within 120min the percentage CO_2 concentration of biogas decreased gradually from 30.71% to 3.96% in case of using NaOH solution and become 6.5% while using $Ca(OH)_2$ solution as shown on the figure 7.1. Therefore, NaOH solution is more efficient and preferable than that of $Ca(OH)_2$ solution.

It can be seen that the concentration of CO_2 reduced sharply in the experiments up to 10 min and after 10 min up to 35 min. Then the concentration trends to decreased gradually and almost remained stable between 60 to 120 min.

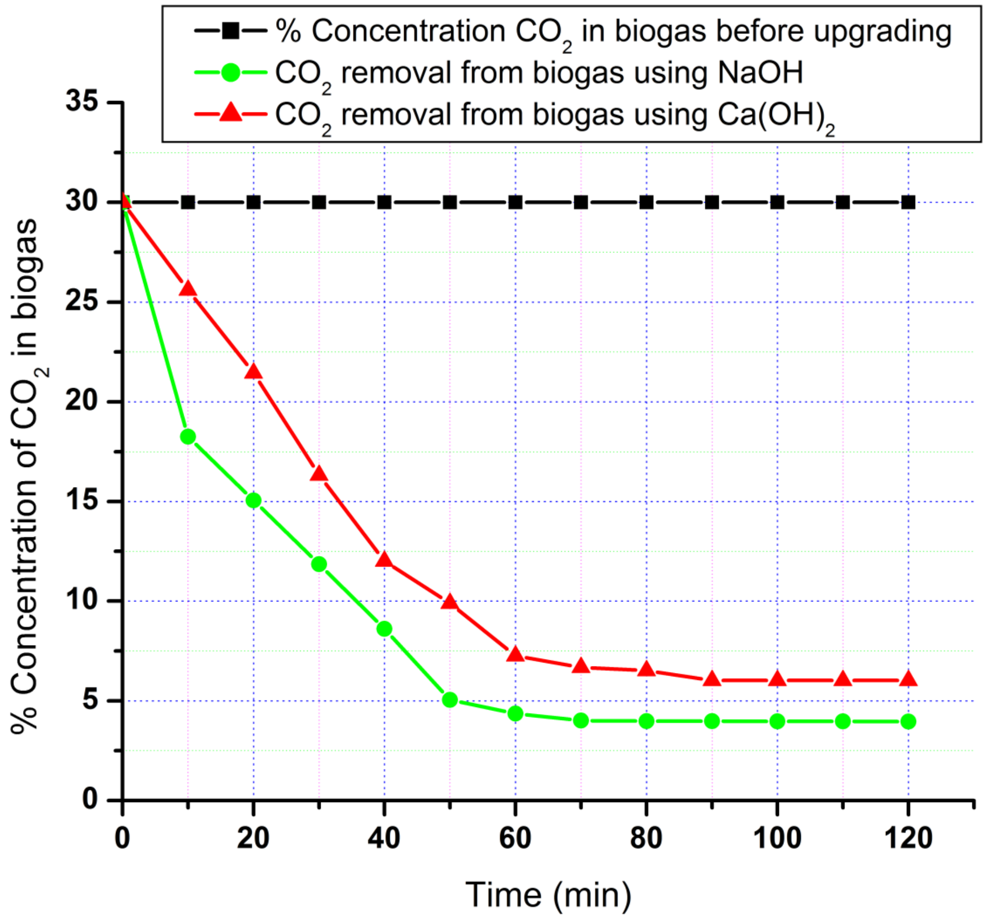


Figure 4. 5: Input and output CO2-concentration of biogas during upgrading

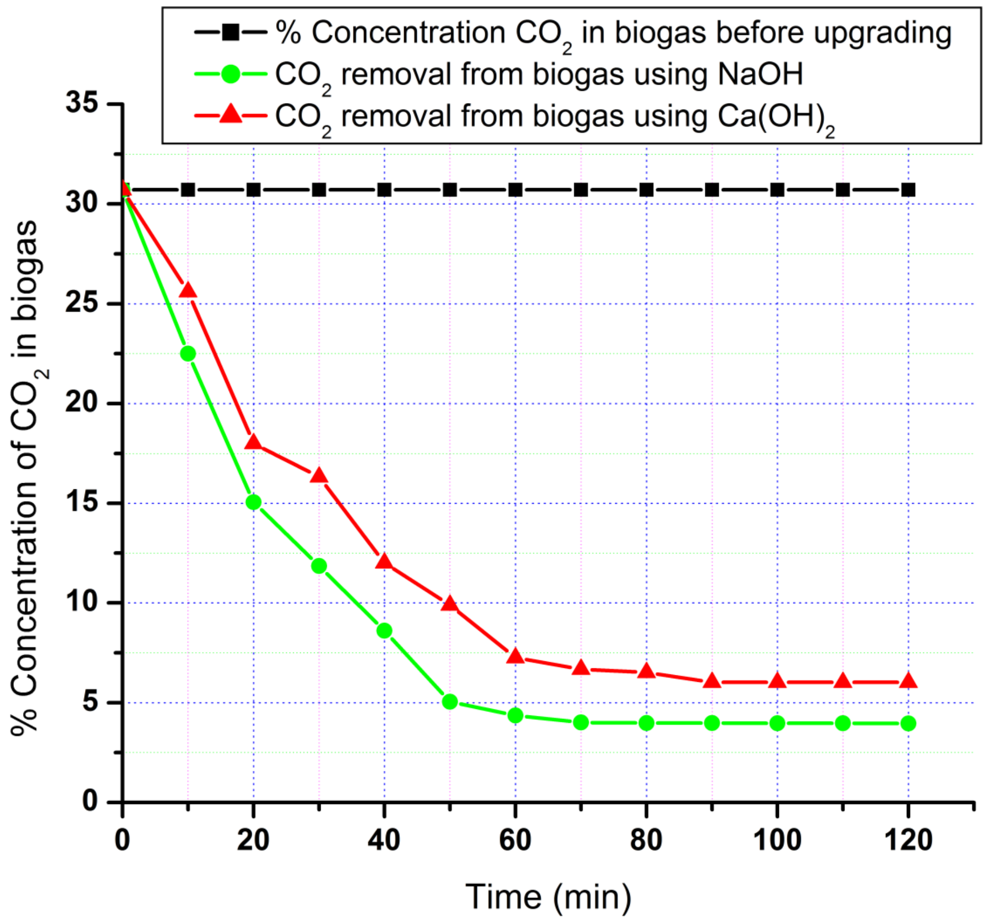


Figure 7. 1: Input and output CO_2-concentration of biogas

7.1.2. Adsorption of water vapor by silica gel

The tests were conducted with the controlled flow rate of biogas directly from the digesters at $5.2m^3/hr$. Here biogas was fed into the adsorption column for 2hr during the test. As time was increased then the concentration of moisture tends to decrease sharply for the first 10 minute and reduced slightly sharp within the next 40min.

The H_2O concentration in the exit from the purified gas-sampling unit was measured using an offline gas analyzer. The resulting breakthrough curves for the H_2O concentration in the exit of biogas became below 1.0% after 40 min and reach 0.18% at 110min while using silica gel and 0.62% in case of sodium sulfate as shown on the figure 7.2, below.

The adsorbent could last until saturation was reached, after which the moisture concentration decreased negligibly. The silica gel might be reactivated after saturation by heating it in an oven at 150℃ for 3hours to remove the adsorbed H_2O and reuse the adsorbent again.

Finally, H_2O concentration remained almost stable between 85 to 120 min and then the experiment was stopped. From the result it is possible understand that silica gel is more efficient and preferable adsorbent than that of sodium sulfate.

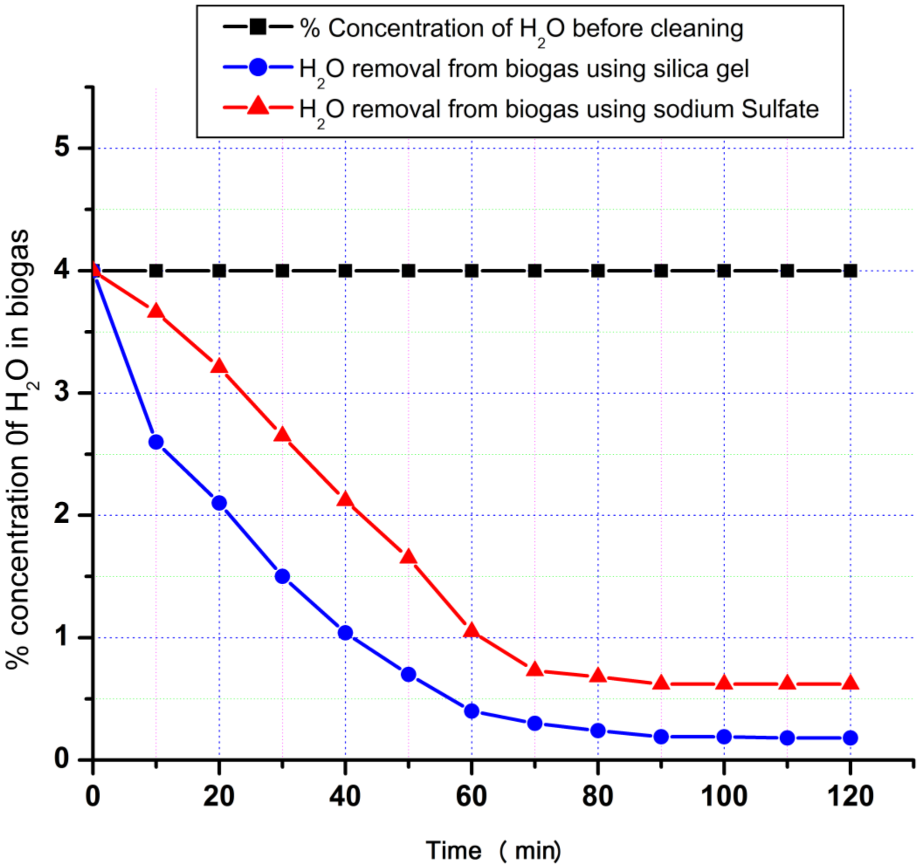


Figure 7. 2: Input and output H_2O-concentration of biomethane

7.1.3. Chemical Adsorption of hydrogen sulfide by activated carbon

After drying process the gas entered in to H_2S scrubber filled by either activated carbon or steel wool. According to the result found from measurement, the breakthrough curve implies that a continuously decrement on H_2S concentration and reach 50 ppm for activated carbon and 100ppm for steel wool. As shown in the figure 7.3, below while using activated charcoal concentration of H_2S reduced sharply for 40 min and slightly faster for the first 25min than that of steel wool. Then H_2S reduction became slightly constant and continued in such manner until the adsorbent became saturated. Finally, reduction was almost become stable between the times from 80 to 120 min.

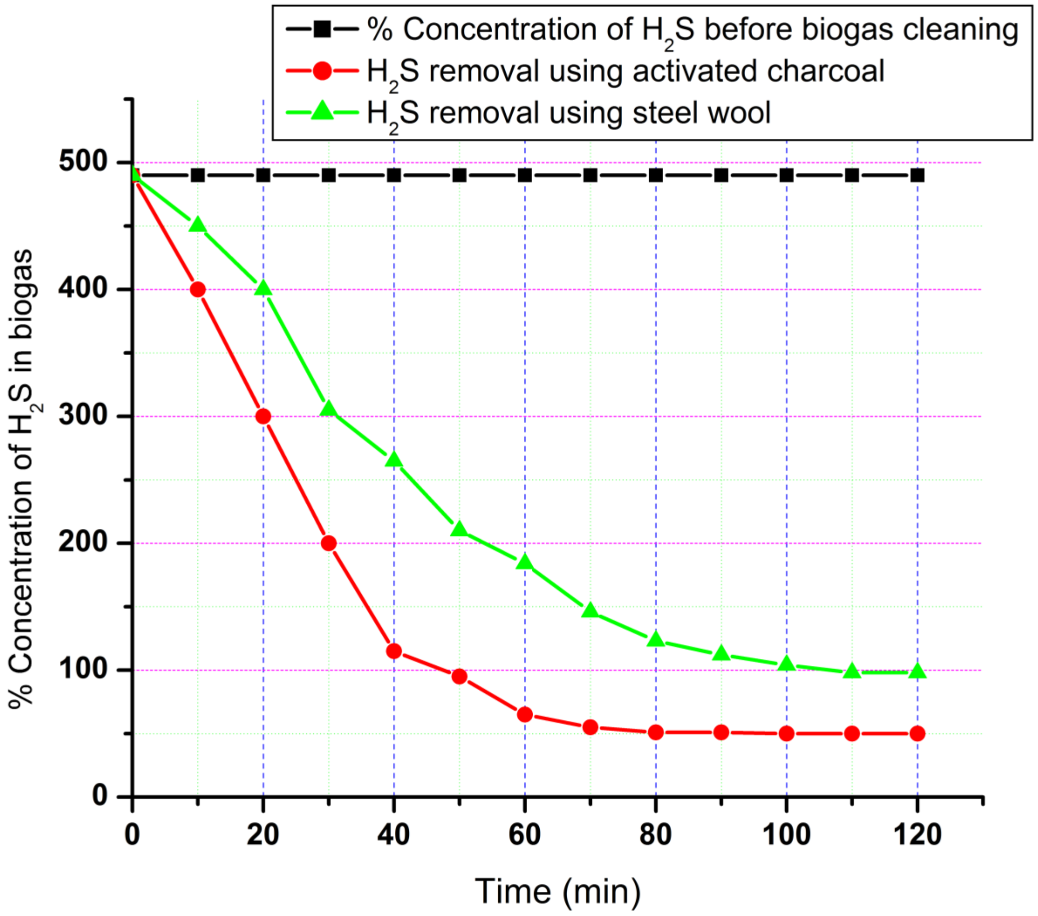


Figure 7. 3: Input and output H_2S-concentration of biomethane

Therefore, it is possible to use the purified gas for running in internal combustion engines because composition of H_2S is below 100ppm, which is acceptable and suitable to use biomethane with minimum risk for human health. The H_2S limit for electricity production by internal combustion engines is 100 ppm [14] [17].

7.1.4. Methane concentration of upgraded biogas

After cleaning and upgrading process, the biogas becomes free from unnecessary gas and becomes CH_4 enriched gas. During the experiment the relative composition of CH_4 gas with respect to time being analyzed. There was a steady increase in CH_4 content up to 50 during while using both NaOH and $Ca(OH)_2$ solution. Then the highest percentage CH_4 concentration of reaches 90% using NaOH solution and 86% during using $Ca(OH)_2$ after treating the gas between the times 100 to 120 min.

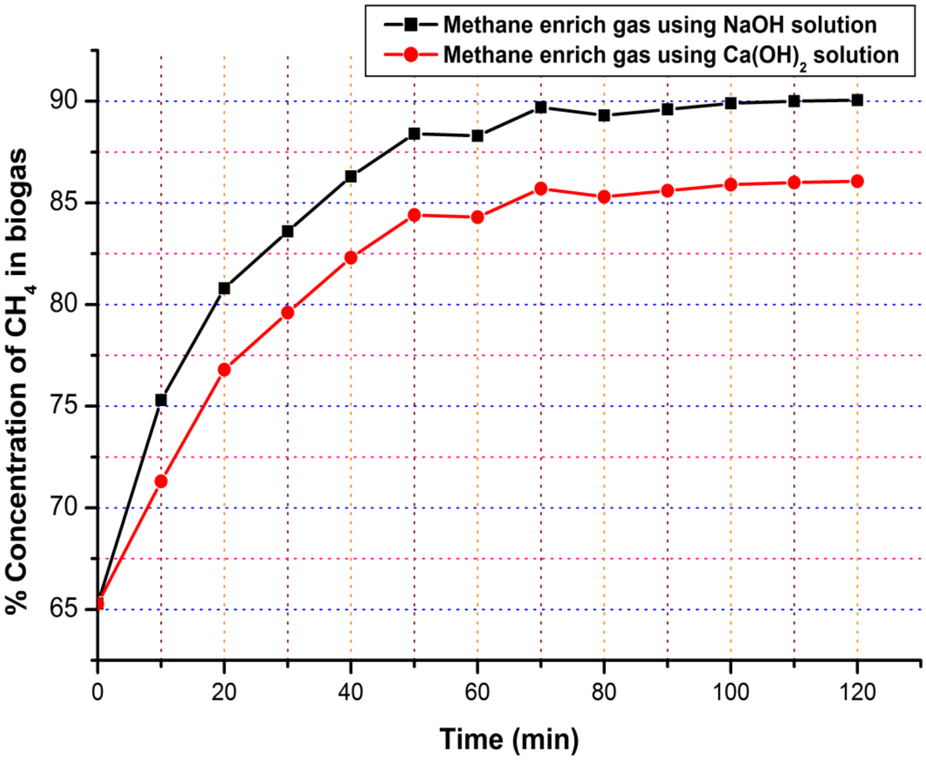


Figure 7. 4: Biogas CH_4 input and output concentration

It is clear from the figure that using sodium hydroxide solution better than other calcium hydroxides solution.

7.1.5. Comparable results of removal efficiency

The H_2S removal efficiency of activated carbon (i.e. $H_2S \geq 90\%$) is more than that of steel wool/iron oxide during the experimental period as shown in figure 7.5. Then the H_2O removal efficiency of silica gel (i.e. $H_2O \geq 95.5\%$) is also higher than that of sodium sulfate. Finally, the CO_2 removal efficiency of NaOH (i.e. $CO_2 \geq 87\%$) is higher than that of $Ca(OH)_2$ .Several tests were conducted to verify reproducibility of the method. The following relation defines the absorption and adsorption efficiency, of chemical scrubber:

$$\eta_f \times y_i = (y_i - y_o) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.1)$$

Where, η_f = absorption and adsorption efficiency

y_i = molar concentration of inlet gas

y_o = molar concentration of inlet gas

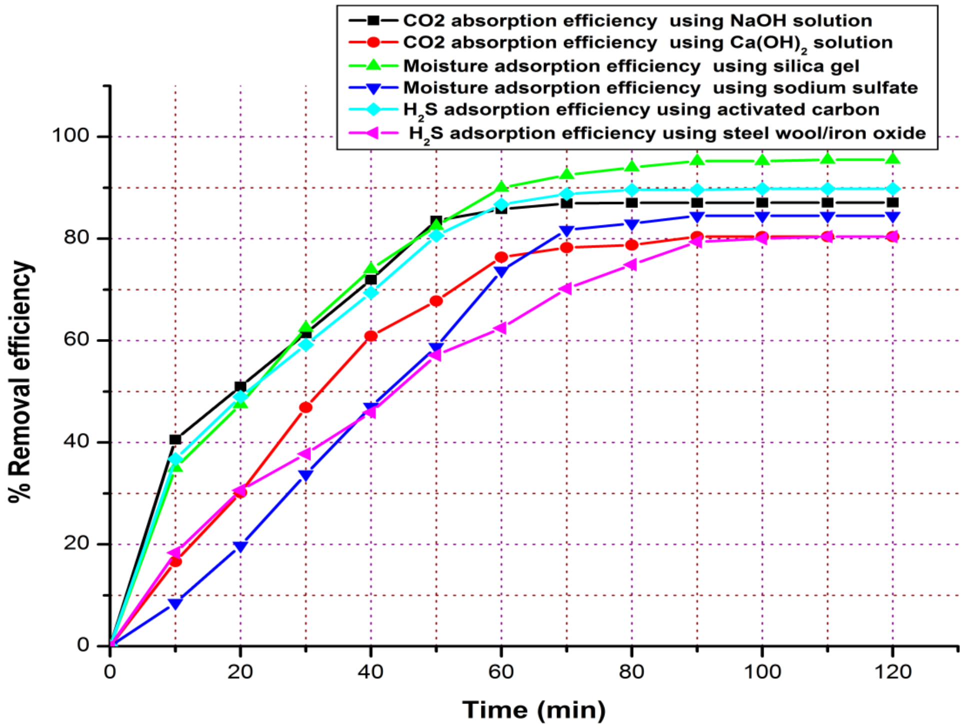


Figure 7. 5: Removal efficiency scrubbing chemicals utilized for biogas purification.

Using Matlab code mass of biomethane produce and amount of chemical required is putted in the figure below based on the experimental data.

- $a\,CH_4 + b\,NaOH/Ca(OH)_2 + c\,C/Fe_2O_3 + d\,SiO_2/Na_2SO_4 \rightarrow XCH_4 + Y\,Na_2CO_3/CaCO_3 + ZH_2O + pS + qFe_2S_3 + rH_2SiO_4$ ……………………………..(7.2)

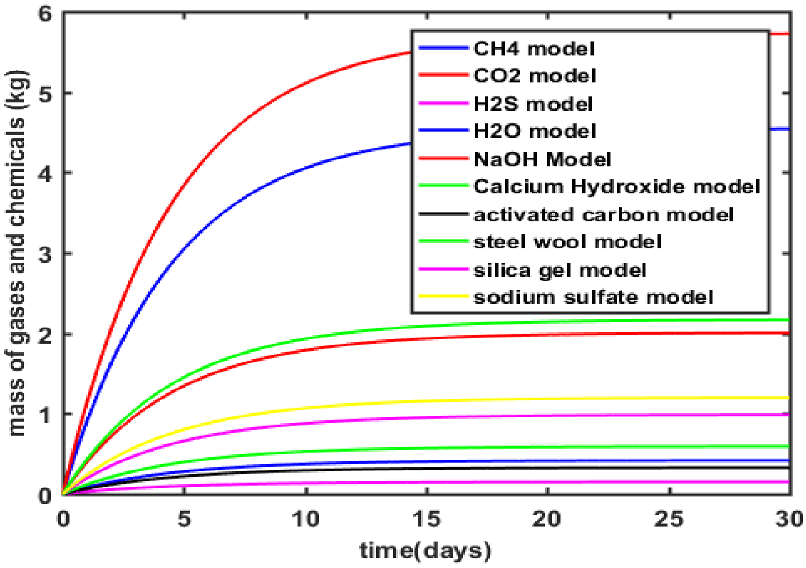


Figure 7. 6. Mass of biomethane produced and chemicals used during upgrading

CHAPTER EIGHT

8. FINANCIAL AND ECONOMIC ANALYSIS

8.1. Introduction

Biomethane is a renewable energy source which environmentally friendly fuel and reduces an expenditure on foreign exchanges while importing petrol and diesel fuels. Even if there is huge potential of biomethane fuel, due to lack of awareness, availability of nonrenewable fuels and relatively high capital investment it is not yet discovered for electricity generation.
Construction and operation of a biogas upgrading plant depends on various technical criteria as well as on a number of economic and utility factors. Therefore, it requires understanding what the plant will offer in the way of gaining profits and advantage like minimized workload, reduced cost for nonrenewable fuel, more reliable and affordable energy supplies or improved health and its sustainability.

8.1.1. Equivalence of biomethane demand

The equivalent demand of biomethane can be determined using the following gasoline and diesel, which can be utilized as a substitute. Therefore, the amount of biomethane produced in each day is equivalent with 7.4-liter gasoline fuel.

Energy source	**Equivalent to 1 Nm^3 of raw Biogas**	**Equivalent to 1 Nm^3 of Biomethane**
Gasoline	(0.53–0.73 lit)	1.10lit
Natural gas	0.45–0.61 m3 (450–610 lit)	0.93 m3 (930L)
Wood coal	0.91–1.24 kg	1.90 kg
Electric energy	4.60–6.20 kWh	9.40 kWh
Mineral coal	0.60–0.82 kg	1.25 kg

Table 8. 1: Biomethane equivalence with some standard fuels [28]

8.1.2. Biomethane demand based on present consumption

It involves measuring the present rate of energy consumption in the form of gasoline fuel. In the university student cafeteria, food is prepared using boiler. In case of electricity problem it is must to use gasoline fuel in order to supply electric power to the boiler and to other electrical appliance. The amount of gasoline fuel and electricity consumed per month is:

1barrel ≅with 159 liter

Energy source	Amount of fuel consumed per month		
	Unit	Price per birr	Average price (in Birr)
Gasoline fuel	2barrel	17	5,406
Electricity	7,009kWh	0.4993	3,500
Total = 8,906Birr			

Table 8. 2: Present energy consumption (Source: field survey, 2017)

8.1.3. Biogas digester construction Materials and Costs

The costs for constructing the proposed design (i.e.10m^3) biogas plant became as follows.

No.	**Item**	**Qty.**	**Price/Cost in Birr**	
			Unit Price	**Total price**
1	Roto tanker	10m^3	42,000	42,000
2	Gasoline silent generator	6kW	40,000	40,000
2	PE plastic Hose(1/2)	100m length and ½ inch diameter	4.8	480
3	Gas pipe	8m length and 10mm diameter	45	360
4	Gate Valve (2 1⁄2 inch)	3	434.78	1,304.34
5	Fiber glass(Pcs)	1	3,913	3913
6	Water Pump	1	2260	2260
7	Empty plastic barrel	1	608.69	608.69
8	Angle iron	2	2500	5000
9	PVC pipe	6	236.52	1,419.12
10	Pressure gauge up to 8 bar	2	900	1800
11	Digital thermometer	0 to 100℃	1,000	1,000
	Sample test	5	2,000	10,000
12	Sand	16m^3	312.5	5,000
13	Cement	18	280	5,000
14	Gravel	16m^3	400	6,400
15	Labor (Machining and Welding)	1	3,000	3,000

16	Payment for labor (construction)	6	1200	6,000
17	U PVC Adapter	2	343.47	686.94
18	Gate Valve (1⁄2 inch)	1	173.91	173.91
19	Postiche	1	130	130
20	Postiche Gun	1	90	90
21	Breaker	1	126.08	126.08
22	Electric motor (for mixing)	1	3800	3800
23	Spray	2	47.82	95.64
24	For transporting material	-	-	5,000
	Total			**145,648.00**
	Contingency 10%			**14,564.80**
	Total money in Birr			**160,212.80**

Table 8. 1: Cost of construction of biogas digester as per the design.

Biogas upgrading material cost:

No.	**Item**	**Qty.**	**Unit price (in birr)**	**Total price (in birr)**
1	Compressor (hermetic)	1	2,000	2,000
2	Water Pump	1	2,260	2,160
3	Sodium Hydroxide	(500g)	450	450
4	Calcium hydroxide	(130kg)	400	400
5	White Silica Gel	(500g)	400	400
6	Activated charcoal powder	500g	450	450
7	PVC pipe for CO_2 scrubber	1.6m and Ø110cm	50	100
8	PPR pipe for moisture removal	0.30m and Ø5cm	50	100
9	PPR pipe for H_2S scrubber	0.30m and Ø5cm	50	100
10	Tyre tube to store biomethane	1	250	250
11	Biogas gas kit (2 liter)	3	22	66
	Total Birr			**6,476**

Table 8. 2: Costs for building biogas-upgrading unit and for chemical required.

8.2. Financial Analysis

Any projects to be considered as economically feasible project its needs to have positive Net Present Value (NPV) and also a payback period is ≤ 7years. The major parameters that need to be considered for the financial feasibility, of biomethane plants are:

8.2.1. Project life

This plant estimated to be lasted for more than 10 years depending on the quality of the materials used. The economic life of a plant is taken as 10 years mainly due to any cost or benefit increased after 10 years will have insignificant value when discounted to the present worth.

8.2.2. Benefits and Cost analysis

The biogas upgrading plants produce both biomethane and organic fertilizer. Biomethane could be used as energy source instead of gasoline and natural gas for electricity generation while organic fertilizer used to improve crops yield, and so could be used in place of manufactured inorganic fertilizers.

In addition, it is important to consider the benefit gained from decreasing environmental population. Therefore, the annual direct financial benefits for plants can be estimated as follows:

$$\mathrm{B_{an}} = \mathrm{B_{anb}} + \mathrm{B_{anf}} - \mathrm{C_{an}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8.1)}$$

$\mathrm{B_{an}} =$ Annual benefit

$\mathrm{B_{anb}} =$ Annual benefit from biomethane

$\mathrm{B_{anf}} =$ Annual benefit from organic fertilizer

$\mathrm{C_{an}} =$ Annual cost

8.2.3. Benefit from Biogas upgrading

According to the design, the amount of biomethane produce with in the entire plant could cover the monthly consumption of gasoline and electricity. Therefore, the annual sum saving expected from using biomethane is Birr 116,592 as shown on Table 8.1 per the cafeteria requirement.

8.2.4. Organic Fertilizer

Another benefit added in to the project is benefit gained from production of organic fertilizer. It can be calculated based on the organic fertilizer gets out from the digester.

Amount of organic matter gets out from digester tank is:

$$O_m = A_L - C_b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8.2)}$$

O_m = Organic matter removes from the digester

A_L = Amounts of substrate loaded

C_b =Organic matter converted in to biogas

$$O_m = A_L - C_b$$

$$= (0.3303 \times 115 \times 30 \times 12) - (0.2 \times 115 \times 30 \times 12)$$

$$= 5{,}394.42\text{Kg per year}$$

Current price of 100kg of manufactured urea fertilizer available in the local markets is reaches about 900Birr. Here organic natter produce per month is 449.53kg. Therefore, by selling the organic matter with 80% discount from urea price then the annual income from selling of 450kg of fertilizer will be:

$$B_{anf} = 0.2 \times 900 \times 4.5 \times 12$$

$$= 9{,}720 \text{ birr per year}$$

8.2.5. Annual Cost

Annual cost for operating a biomethane plant may come from maintenance cost and operational cost. The main operational cost is the cost of power required for compressor and pump. In addition, there is cost during purchasing scrubbing chemicals for the system. The power required for compressor and pump is 0.55kW and 0.60kW respectively. And they are expected to operate for 9 Hour with 4.95kWh and 5.4kWh in each day.

This amount of energy can be provided from either Ethiopia Electric Light and Power Authority (EEPCO) or the plant itself. As it is known, 1m^3 biomethane can generate 4.9kW hours of electricity. Therefore, it is better to use the power from (EEPCO) rather than using power from the system. However, it is possible to use system power if there is electricity problem from main supplying grid.

Currently, EEPCO charges for power as follows:

a) For less than 50 kWh it charges 0.273Birr/ kWh
b) 50 to 100 kWh it charges 0.354 Birr/ kWh
c) For greater than 100 kWh it charges 0.4993Birr/ kWh

According to (EEPCO) the annual cost for the compressor (C_{op}) and pump (P_{op}) operations are determined as:

$$\mathrm{C_{op}} = 4.95\mathrm{kWh} \times 0.273\mathrm{Birr/kWh} \times 365$$

=334.8 Birr per year

$$\mathrm{P_{op}} = 5.4\mathrm{kWh} \times 0.273\mathrm{Birr/kWh} \times 365$$

=538.08 Birr per year

During clean and upgrade biogas, three basic chemical compounds are utilized. These chemicals are calcium hydroxide $\mathrm{Ca(OH)_2}$, Silica gel and activated carbon. Here annual costs of scrubbing chemicals are calculated based on their current price shown in table 8.4 as follow.

$$\mathrm{C_{ch}} = (\mathrm{C_{Ca(OH)_2}} + \mathrm{C_{SiO_2}} + \mathrm{C_{act}}) \times 12 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8.3)}$$

$\mathrm{C_{ch}}$ = annual cost of all chemical

$\mathrm{C_{Ca(OH)_2}}$ = monthly cost for sodium hydroxide

$\mathrm{C_{SiO_2}}$ = monthly cost for silica gel

$\mathrm{C_{act}}$ = monthly cost for activated carbon

$$\mathrm{C_{ch}} = (198 + 800 + 900) \times 12$$

$$= 22{,}776 \text{ Birr per year}$$

Therefore, the total cost became the sum of the operational and maintenance cost.

$\mathrm{C_{an}} = \mathrm{C_{op}} + \mathrm{P_{op}} + \mathrm{C_{ch}} + \mathrm{C_m}$, where $\mathrm{C_m}$ is maintenance cost

$$\mathrm{C_{an}} = 334.8 + 538.08 + 22{,}776 + 15{,}000 = 38{,}646.9\mathrm{Birr}$$

As the result, the annual income will be:

$$\mathrm{B_{an}} = \mathrm{B_{anb}} + \mathrm{B_{anf}} - \mathrm{C_{an}}$$

$\mathrm{B_{anb}} = 106{,}872\mathrm{Birr}$, where from table

$$\mathrm{B_{an}} = 106{,}872 + 9{,}720 - 38{,}646.9\mathrm{Birr} = 77{,}945.1 \text{ Birr}$$

8.2.6. Cash Flow Analysis

Simple procedure of cash flow by entering all the year-by-year income to be gained over the estimated life of the project as inflows. As the same time, the yearly expenditures are entered in the analysis as outflow. At the end, for each year, expenditure is deducted from the income. Therefore, in the initial year of the project, the net cash flow or net benefit tends to be negative; this is due to the expenditures incurred to meet the establishment costs.

8.2.7. Time Value of Money

A Birr received now is more valuable than a Birr to be received one year from now because of the investment possibilities that are available for today's Birr. Real value of money changes over time[67]. The reasons for such changes are:

- ✓ As a businessperson, any person lives in an uncertain world.
- ✓ Money of today can be invested to earn a return in the future; and
- ✓ People have time preference, i.e. they prefer now to the future.

8.2.8. Net Present Value

As the costs and benefits of a project are spread over the useful years of project life, they need to be expressed in terms of one common denominator to make the comparison possible. Once the annual cash flow of a project is derived, it needs to be discounted so that all values could be compared to the value of a single year. This discounted net cash flow provides a widely used criterion for measuring the profitability of a project. For this purpose, all future values are discounted to make them equivalent to the present value and is expressed as Net Present Value (NPV) [67].

The NPV technique measures the worthiness of a project by converting the annual cash flow to a single present value.

When NPV	The project
= 0	Just enough to recoup the capital invested
>1	Benefits are higher than the costs
<1	Has no ability to return the invested capital

Table 8. 3: The NPV technique measures the worthiness of a project[41].

The process of relating future amount to the present value is known as discounting and is expressed by the following equation:

$$P = \frac{F}{(1+r)^n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8.5)}$$

Where, P = present sum of money

F = Future sum of money

r = Rate of interest

n = Number of years

8.2.9. Simple Payback Period

It is required period time which is important to return the original investment for the construction of a plant. It represents the number of years in which the investment is expected to pay for itself. It is given by:

$$\mathrm{SPP} = \frac{\mathrm{I_c}}{\mathrm{A_s}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8.6)}$$

Where, SPP = Simple payback period

$I_c =$ Initial cost

$A_s =$Annual saving (benefits)

8.2.10. Benefit Cost Ratio

Benefit-cost ratio (BCR) is another tool for assessing the profitability of a project. If the ratio is greater than unity (i.e. B/C > 1.0), the project is profitable.

$$\mathrm{BCR} = \frac{\mathrm{P_B}}{\mathrm{P_C}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8.7)}$$

8.3. Economic Analysis

Economic analysis primarily measures the effect of biogas upgrading programme on the fundamental objectives of the whole economy. This is because of a single biogas upgrading plant does not significantly affect the economy as a whole. However, the campus community will also be benefited through environmental protection from pollution and conservation the compound even if they are not subject matter of financial analysis

Years	1	2	3	4	5	6
Gasoline Saving	64,872	64,872	64,872	64,872	64,872	64,872
Electricity Saving	42,000	42,000	42,000	42,000	42,000	42,000
Selling organic fertilizer	9,720	9,720	9,720	9,720	9,720	9,720
Total	116,592	116,592	116,592	116,592	116,592	116,592
Costs(in Birr)						
Investment	165,788.8					
Maintenance	15,000	15,000	15,000	15,000	15,000	15,000
Operation cost	23,648.9	23,648.9	23,648.9	23,648.9	23,648.9	23,648.9
Total	204,437.7	38,646.9	38,646.9	38,646.9	38,646.9	38,646.9
Net Benefit (in Birr)	**-87,845.7**	**77,945.1**	**77,945.1**	**77,945.1**	**77,945.1**	**77,945.1**

Table 8. 4: Financial analysis of a biomethane including biogas production

The net present value, benefit cost ratio and simple payback period are determined as follows. The present value of benefits or saving during the lifetime of the project at r = 12% can be determined as follow:

$$P_B = A_B \left[\frac{(1+r)^n-1)}{r(1+r)^n}\right] \text{...} (8.7)$$

A_B = Annual benefits

P_B = Total benefits during the lifetime of the project

$$P_B = 116{,}592 \times \left[\frac{(1+0.12)^7-1)}{0.12\times(1+0.12)^7}\right]$$

$$= 532{,}097.5 \text{ Birr}$$

The present costs during the lifetime of the project are determined as

$$P_C = I_C + A_C\left(\frac{P}{A_C}, r, n\right) \text{...} (8.8)$$

P_C = Total cost

I_C = Initial cost

A_C = Annual cost

r = Discount rate

Where:

$$P_C = 165{,}788.8 + 38{,}646.9 \times \left[\frac{(1+0.12)^7 - 1)}{0.12 \times (1+0.12)^7}\right]$$

$$= 342{,}163.8\text{Birr}$$

The Net Present Value is:

$$\text{NPV} = P_B - P_C$$

$$= 532{,}097.5 \ - 342{,}163.8\text{Birr}$$

$$= 189{,}933.7 \text{ Birr}$$

The annual saving is:

$$A_S = A_B - A_C$$

$$A_S = 116{,}592 - 38{,}646.9$$

$$= 77{,}945.1 \text{ Birr}$$

The simple payback period is:

$$\text{SPP} = \frac{I_c}{A_s} = \frac{165{,}788.8}{77{,}945.1} = 2.12 \text{ years}$$

This implies the investment will return the capital of constructing biogas-upgrading plant with in a time of less than three years.

The benefit cost ratio

$$\text{BCR} = \frac{P_B}{P_C} = \frac{532{,}097.5}{342{,}163.8} = 1.55 > 1$$

Therefore, the project is profitable because benefit-cost ratio is greater than 1.0.

CHAPTER NINE

9. CONCLUSION AND RECOMMENDATION

9.1. Conclusion

Biogas upgrading is a technique applied to remove CO_2 and include removal of moisture and unwanted gaseous substance from produced biogases. This is done in order to enrich the methane content with the objective of increasing the calorific value of the gas. Biomethane is a renewable and environmentally friendly energy source, which will be used to generate electricity and produce heat for different purpose.

The study will help Addis Ababa Sidist kilo campus to produce 10.35m^3 biomethane from converting the 115 kg/day food waste. This 10.35m^3/day biomethane can be converted to 6.1kW electricity that could be used for the student cafeteria.

The experiment for cleaning and upgrading was conducted with two possibilities. These are using silica gel, activated carbon, and sodium hydroxide in one side and sodium sulfate, steel wool/iron oxidized and calcium hydroxide on the other side. The result obtained from the experiment is recorded and compared after that the silica gel, activated carbon and sodium hydroxide become suitable choice for biogas upgrading.

After purification, biomethane gas tested using gasoline generator, during the test the ammeter and voltmeter reading on the generator displays 27A and 220V electricity.

The cafeteria will be benefited from biogas conversion in to biomethane, which is natural gas standard gas comparable energy source with gasoline. The biomethane from food waste has potential to 6.1kW generator to operate at list for 9 hours per day. In addition, the cafeteria gets advantage from reduction of cost of gasoline that is used to generate electricity to produce steam in boiler during cooking and to operate other electric appliance.

This model predicts that the rate and composition of purified gas with respect to time. In addition, it helps to predict the amounts of adsorbed and absorber chemical.

This thesis is important to minimize environmental pollution i.e. reduces contribution for greenhouse effect and disease carrier organisms and unpleasant odor, which has long term effect on campus societies.

Financially the research indicates that net present value of the plant is 189,933.7 Birr which is positive and can be increases if the cafeteria maximize its waste utilization potential and benefit cost ratio is 1.55 which is greater than one and the simple payback period is 2 years and two months.

9.2. Recommendation

For near future the present research can be upgraded using chemical simple to regeneration process, which minimizes cost of upgrading. Furthermore, for rural areas, which have shortage in chemical absorber, it is possible to use water scrubber to upgrade biogas and extract maximum amount of energy from it. Here economically viable project ideas are suggested:-

- ✓ Upgrading and liquefying biogas, to use it for vehicle fuel, which is marketable, economically feasible, and help the country to minimize foreign expense for fossil fuel.
- ✓ Biogas upgrading for direct electricity using fuel cell.

Bibliography

[1] S. Cvetković, T. K. Radoičić, and B. Vukadinović, “Environmental Effects A life cycle energy assessment for biogas energy in Serbia,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 38, no. 20, pp. 3095–3102, 2016.

[2] K. C. Surendra, D. Takara, A. G. Hashimoto, and S. Kumar, “Biogas as a sustainable energy source for developing countries : Opportunities and challenges,” *Renew. Sustain. Energy Rev.*, vol. 31, pp. 846–859, 2014.

[3] D. O. Okuo, M. A. Waheed, and B. O. Bolaji, “Evaluation of Biogas Yield of Selected Ratios of Cattle , Swine , and Poultry Wastes,” *Int. J. Green Energy*, vol. 13, no. 4, pp. 366–372, 2016.

[4] A. Yousuf, M. R. Khan, D. Pirozzi, and Z. Ab, “Financial sustainability of biogas technology : Barriers , opportunities , and solutions,” *Energy Sources, Part B Econ. Planning, Policy*, vol. 11, no. 9, pp. 841–848, 2016.

[5] R. P. Agrahari and G. N. Tiwari, “The Production of Biogas Using Kitchen Waste,” vol. 3, no. 6, pp. 408–413, 2013.

[6] M. Verotti, P. Servadio, and S. Bergonzoli, “Biogas upgrading and utilization from ICEs towards stationary molten carbonate fuel cell systems fuel cell systems,” *Int. J. Green Energy*, vol. 13, no. 7, pp. 655–664, 2016.

[7] L. M. Kamp, “BOTTLENECKS AND DRIVERS IN ETHIOPIA ’ S DOMESTIC BIOGAS SECTOR,” no. 1, pp. 1714–1742, 2015.

[8] A. Joshi, J. Jose, N. Bansiwal, and N. Soni, “Study on Electricity Generation through biogas on small scale,” pp. 6662–6669, 2017.

[9] M. Mel and M. S. Jami, “A review of chemical absorption of carbon dioxide for biogas upgrading,” no. May, 2016.

[10] W. Kordylewski, D. Sawicka, and T. Falkowski, “Laboratory tests on the efficiency of carbon dioxide capture from gases in NaOH solutions,” vol. 14, no. 2, pp. 54–62, 2013.

[11] F. R. H. Abdeen, M. Mel, M. S. Jami, S. I. Ihsan, and A. F. Ismail, “Chinese Journal of Chemical Engineering A review of chemical absorption of carbon dioxide for biogas upgrading,” *CJCHE*, vol. 24, no. 6, pp. 693–702, 2016.

[12] S. Production, “DUAL-FUEL LOW POWER GENERATOR WITH DIESEL ENGINE,” vol. 19, no. 3, 2012.

[13] M. Rashed, A. Mamun, and S. Torii, “Removal of Contaminant Gases from Biogas by

Chemical Purification Processes," vol. 3, no. 10, pp. 12–20, 2015.

[14] S. D. R, N. H. J, and A. Pradeep, "Purification of Biogas using Chemical Scrubbing and Application of Purified Biogas as Fuel for Automotive Engines," vol. 5, pp. 1–7, 2016.

[15] H. S. Salave and A. D. Desai, "Design , Development and Experimental Investigation on Various Biogas Upgrading Techniques," no. March, pp. 55–60, 2017.

[16] M. Rashed and A. Mamun, "Enrichment of Methane Concentration by Removing Contaminant Gases from Biogas Mixtures Based on Chemical Purification Processes," no. February, 2017.

[17] D. Shah and P. H. Nagarseth, "Low Cost Biogas Purification System for Application Of Bio CNG As Fuel For Automobile Engines," vol. 2, no. 6, pp. 308–312, 2015.

[18] M. Farooq, I. A. Chaudhry, S. Hussain, N. Ramzan, and M. Ahmed, "BIOGAS UP GRADATION FOR POWER GENERATION APPLICATIONS IN PAKISTAN 1) INTRODUCTION," vol. VIII, no. Ii, pp. 107–118, 2012.

[19] E. Chen and K. Rolin, "Activated Carbon-based Carbon Dioxide Adsorption Process Activated Carbon-based Carbon Dioxide Adsorption Process," 2017.

[20] V. R. Gaikwad, "Biogas Compression and Bottling : A Solution to Energy Crises," pp. 13–16.

[21] B. Journal, "INVESTIGATION OF IMPREGNATED ACTIVATED CARBON PROPERTIES USED IN HYDROGEN," vol. 33, no. 04, pp. 1021–1030, 2016.

[22] I. Wheeldon *et al.*, "Utilization of Biogas Generated from Ontario Wastewater Treatment Plants in Solid Oxide Fuel Cell Systems : A Process Modeling Study UTILIZATION OF BIOGAS GENERATED FROM ONTARIO WASTEWATER TREATMENT PLANTS IN SOLID OXIDE FUEL CELL SYSTEMS : A PROCESS MODE," vol. 5075, no. November, 2016.

[23] V. Vaid and S. Garg, "Food as Fuel : Prospects of Biogas Generation from Food Waste 4 meter cube Biogas," vol. 4, no. 2249, pp. 68–71, 2013.

[24] A. Pourmovahed, D. Ph, T. Opperman, and B. Lemke, "Performance and Efficiency of a Biogas CHP System Utilizing a Stirling Engine Advantages of the Stirling Engine," vol. 1, no. 9, pp. 202–207, 2011.

[25] E. Science, "Production of Biogas from wastes Blended with CowDung for Electricity generation-A Case study Production of Biogas from wastes Blended with CowDung for Electricity generation-A Case study," 2017.

[26] P. Cozma and W. Wukovits, "Modeling and simulation of high pressure water

scrubbing technology applied for biogas upgrading,” pp. 373–391, 2015.

[27] D. R. Shah and P. H. J. Nagarsheth, “Biogas Up Gradation using Water Scrubbing for its use in Vehicular Applications,” vol. 2, no. 6, pp. 2393–2395, 2015.

[28] N. Khandaker and P. Seto, “Novel Application of Vermiculite for Siloxane Removal from Biogas,” vol. 5075, no. November, 2016.

[29] L. Megido, E. Marañón, L. Castrillón, L. Negral, and P. Ormaechea, “Optimization of biogas upgrading by absorption of CO 2 into ethanolamine solution,” pp. 1–8.

[30] E. H. M. Dirkse, “‘ Biogas upgrading : Membrane separation takes over ’ - The success story of Poundbury continues - Langerak , J ., Lems , R ., Giménez Domínguez P ., Dirkse E . H . M .,” pp. 1–9.

[31] A. N. E. Approach, *Cengel & Boles - Thermodynamics_ An Engineering Approach 8th Edition c2015 txtbk.* .

[32] J. Fournier, “ScienceDirect ScienceDirect Development Biogas Purification 15th International of Development of Biogas Purification System Using Calcium Hydroxide and Amine Solution Using Calcium Hydroxide and Amine Solution Assessing the feasibility of using the a heat,” *Energy Procedia*, vol. 138, pp. 441–445, 2017.

[33] T. Gde *et al.*, “Method on Conversion of Gasoline to Biogas Fueled Single Cylinder of Four Stroke Engine of Electric Generator,” vol. 4, no. 3, 2013.

[34] C. Chang *et al.*, “Electricity Generation Using Biogas From Swine Manure for Farm Power Requirement Electricity Generation Using Biogas From Swine Manure for Farm Power Requirement,” *Int. J. Green Energy*, vol. 12, no. 00, pp. 339–346, 2016.

[35] W. Uddin *et al.*, “Biogas potential for electric power generation in Pakistan : A survey,” *Renew. Sustain. Energy Rev.*, vol. 54, pp. 25–33, 2016.

[36] E. Svanes and K. Silvennoinen, “Standard approach on quantitative techniques to be used to estimate food waste levels Status : Final,” no. July, 2014.

[37] M. Fedailaine, K. Moussi, M. Khitous, S. Abada, M. Saber, and N. Tirichine, “Modeling of the anaerobic digestion of organic waste for biogas production,” *Procedia - Procedia Comput. Sci.*, vol. 52, no. Seit, pp. 730–737, 2015.

[38] F. Mairet, O. Bernard, M. Ras, L. Lardon, and J. Steyer, “Bioresource Technology Modeling anaerobic digestion of microalgae using ADM1,” *Bioresour. Technol.*, vol. 102, no. 13, pp. 6823–6829, 2011.

[39] A. B. Aderibigbe, “DESIGN AND CONSTRUCTION OF 250 LITERS PLASTIC BIO-DIGESTER AND EVALUATION OF BIOGAS PRODUCTION USING 4 CO-SUBSTRATES IIOAB-India,” 2015.

[40] S. M. Sain and N. A. A, “Thermal Simulation of Biogas Plants Using Mat Lab,” vol. 4, no. 10, pp. 24–28, 2014.

[41] R. Namuli, C. B. Laflamme, and P. Pillay, “A Computer Program for Modeling the Conversion of Organic Waste to Energy,” pp. 1973–2001, 2011.

[42] N. Riar and S. Kumar, “A Study of Treatability of Kitchen Wet Waste And Biogas Production,” pp. 62–65, 2013.

[43] M. Gedefaw, “Biogas production from cow dung and food waste,” vol. 3, no. 1, pp. 103–108, 2015.

[44] K. C. Surendra *et al.*, “Household anaerobic digester for bioenergy production in developing countries : opportunities and challenges,” vol. 3330, no. November, 2016.

[45] P. C. Ghimire, “SNV supported domestic biogas programmes in Asia and Africa,” *Renew. Energy*, vol. 49, pp. 90–94, 2013.

[46] K. Mushtaq, A. A. Zaidi, and S. Jawid, “Design and performance analysis of floating dome type portable biogas plant for domestic use in Pakistan,” *Sustain. ENERGY Technol. ASSESSMENTS*, vol. 14, pp. 21–25, 2016.

[47] M. Das Ghatak and P. P. Mahanta, “Biogas Purification using Chemical Absorption,” vol. 8, no. 3, pp. 1600–1605, 2016.

[48] M. A. Olutoye and A. Mohammed, “Modelling of a Gas-Absorption Packed Column for Carbon Dioxide-Sodium Hydroxide System,” vol. 10, no. October, pp. 132–140, 2006.

[49] F. Edition, *Chemical engineering design*. .

[50] V. S. Accessories, “COMPRESSORS STEPS TO COMPRESSOR SELECTION & SIZING Understand the Application What is the compressor supposed to do ?”

[51] V. R. Gaikwad and P. K. Katti, “Design of Biogas Scrubbing , Compression & Storage System,” pp. 58–63, 2014.

[52] S. Z. Ilyas, “A Case Study to Bottle the Biogas in Cylinders as Source of Power for Rural Industries Development in Pakistan,” vol. 1, no. 2, pp. 127–130, 2006.

[53] C. P. K. A. R.RUDRAMOORRTHY, “Fluid Mechanics and Machinary,” Second., New Delhi, 2007, p. 226.

[54] J. P. Holman and J. Lloyd, *Fluid Mechanics*. .

[55] F. P. I. & D. P. Dewiti, *No Title*. .

[56] H. N. Prajapati, T. M. Patel, and G. P. Rathod, “Performance analysis of biogas premixed charge diesel dual fuelled engine,” vol. 11, no. 3, pp. 8–12, 2014.

[57] G. Singh, A. Singh, and V. K. Jain, “Economic Viability of Biogas Generator in

Comparison with Diesel Generator and Local Electricity Connection," vol. 9359, no. 7, pp. 40–43, 2013.

[58] B. Nkoi, B. T. Lebele-alawa, and P. Harcourt, "Comparative Assessment of Combined-Heat-and-Power Performance of Small-Scale Aero-Derivative Gas Turbine Cycles," no. September, pp. 20–32, 2015.

[59] E. Procedia, "Simple Conversion Method from Gasoline to Biogas Fueled Small Engine to Powered Electric Generator Simple Conversion Method from Gasoline to Biogas Fueled Small Engine to Powered Electric Generator," no. December, 2014.

[60] L. I. Yingjian, Q. I. U. Qi, H. E. Xiangzhu, and L. I. Jiezhi, "Energy use project and conversion efficiency analysis on biogas produced in breweries," pp. 1489–1496.

[61] S. Arali, "Design and Development of Intake Device for Biogas operated 4-Stroke SI ScienceDirect Design and Development of Intake Device for Biogas operated 4-Stroke SI Engine," no. January 2018, 2016.

[62] N. K. Lasmi, A. Singarimbun, and L. W. Srigutomo, "The Improvement of Carburater Efficiency Using Biogas- based Venturi," vol. 01018, pp. 0–5, 2016.

[63] K. von Mitzlaff, *Engines for Biogas*. Federal Republic of Germany., 1988.

[64] V. E. Ijifr, "Design Of Intake System For Biogas Fuelled SI Engine," vol. 3, no. 11, pp. 4181–4187, 2016.

[65] M. S. Shah, P. K. Halder, A. S. M. Shamsuzzaman, M. S. Hossain, S. K. Pal, and E. Sarker, "Perspectives of Biogas Conversion into Bio-CNG for Automobile Fuel in Bangladesh," vol. 2017, 2017.

[66] Bimal K. Bose, *Power Electronics and Motor drives*, Third edit. New York: The University of Tennessee, 2006.

[67] D. CUCCHIELLA, F., Adamo, "A profitability analysis of small-scale biomethane plants," pp. 7–8.

Appendix

1. Multiquip Honda engine Recoil start Portable Generator Specifications (Source. www.multiquip.com)

MODEL	GAC22H	GAC36HZ	GAC6HZR	GAC6HZ	GAC97HZ	DAC7000SSA
Rated power (kW)	2,200	3,600	6,000	6,000	9,700	7,000
Voltage (V)	120	120/240V				
Frequency (Hz)	50/60Hz					
Rated Speed (rpm)	3600					
Amp @ 120V	18	15*2	25*2	25*2	40*2	29.2*2
Amp @ 240V		15	25	25	40	29.2
Phase/No. pole	Single phase (1 pole)	Single phase (2 pole)				
Manufacturer	Honda	Honda	Honda	Honda	Honda	Honda
Fuel Capacity	13.6	18.9	18.9	18.9	37.8	24.4
DIMENSIONS	(605×445×445) mm^3					

2.Water Electric Pumps Catalogue 50Hz (Source, www.tumapumpen.at)

MODEL	**Power Rating (P)**		**Total head in meter**															
	kW	HP	40	38	36	34	32	30	28	26	24	22	20	18	16	14	12	10
			Discharge in liter per minute															
HL23	0.37	0.5											8	10	13	16	20	25
HL35	0.3	0.4				2	4	7	9	12	15	19	24	36	42	45	46	48
HL37	0.37	0.5			2	3	7	11	17	18	24	30	37	42	45	48	49	51
HL42	0.6	0.8	2	7	12	18	24	28	33	36	39	42	45	46	48	50	51	52
HL32MS	0.75	1						16	27	38	44	48	53	57	60	63	66	70
HL42MS	1.1	1.5	18	24	30	36	42	45	48	51	54	57	60	63	66	69	72	75
HL52MS	1.1	1.5	41	44	48	51	54	56	59	62	63	65	67	69	71	72	74	

3. Instruments and Chemical used during the experimental analysis

 Fiber glass roto tanker (biogas digester)	 Moisture and hydrogen sulfide scrubber
 Thermostat-heater	 Tyre tube
 Hermetic compressor	 Corbondioxide scrubber

Activated charcoal

Sodium hydroxide

Silica gel

Glue gun

4. Specification and accuracy of measuring instrument used

Specification and accuracy	Instrument used
1. Max. capacity 1000gram 2. Digital type 3. Accuracy ±0.1gram	 Digital scale weight balance
1. Max. capacity =400kPa 2. Analog type 3. Accuracy = ±1%	 Pressure gauge
1. Detection principle: Electro-chemistry and catalytic 2. Detection accuracy = ±3% 3. Humidity detection from 0-95% non- condensing 4. Reaction time with: O_2 =10 second CO_2 =10 second H_2S = second	 Portable gas analyzer
1. Measure 2000mL 2. Accuracy ±2%	 Air bag (Biogas gas kit)

5. Sample collected from Addis Ababa campus.

Sample 1:

	Enjera + wot (kg)									
Date	**Week1**	**Week2**	**Weak3**	**Week4**	**Week5**	**Weak6**	**Week7**	**Week8**	**Total**	**Mean**
Monday	100	98	99	103	105	97	100	98	800	100
Tuesday	103	105	104	106	107	103	105	107	840	105
Wednesday	100	102	101	100	102	101	100	102	808	101
Thursday	101	100	100	101	98	99	100	101	800	100
Friday	104	106	104	105	103	108	104	106	840	105
Saturday	100	99	102	101	99	100	99	100	800	100
Sunday	110	107	109	110	112	110	113	109	880	110

With standard deviation of SD = 2.75.

Sample 2:

	Bread(kg)									
Date	**Week1**	**Week2**	**Weak3**	**Week4**	**Week5**	**Weak6**	**Week7**	**Week8**	**Total**	**Mean**
Monday	5	4	5	4	6	5	6	5	40	5
Tuesday	6	8	7	7	6	7	8	7	56	7
Wednesday	5	7	6	6	7	6	5	6	48	6
Thursday	5	4	5	5	6	5	6	4	40	5
Friday	6	7	5	7	6	6	5	6	48	6
Saturday	5	5	4	6	6	4	5	5	40	5
Sunday	8	7	7	6	7	6	7	8	56	7

With standard deviation of SD = 0.756

Sample 3:

	Wot(kg)									
Date	**Week1**	**Week2**	**Weak3**	**Week4**	**Week5**	**Weak6**	**Week7**	**Week8**	**Total**	**Mean**
Monday	7	6	7	8	7	6	7	8	56	7
Tuesday	6	7	5	6	7	6	5	6	48	6
Wednesday	6	5	6	7	6	5	6	7	48	6
Thursday	5	6	4	6	5	5	4	5	40	5
Friday	7	8	6	7	6	7	8	7	56	7
Saturday	5	6	7	6	5	6	7	6	48	6
Sunday	7	6	5	7	6	5	6	6	48	6

With standard deviation of SD = 0.748

5. Matlab Simulation for 115 Kg/day Input

```
%1. MATLAB SIMULATION FOR 115 Kg/day INPUT
% This code helps to calculate chemical model needed for purification and amount
% of gas production
%% Sizing of Biogas
prompt = 'Insert Daily input in Kg? ';
Daily input = input(prompt);
prompt = 'Insert Retention Time_No of days? ';
RT = input(prompt);
prompt = 'Insert Concentration_of_TS? ';
Concentration_of_TS = input(prompt);
TS=(Dailyinput)*0.3033;
water_required = (TS/Concentration_of_TS)-(Dailyinput);
Total_influent_required = (TS/Concentration_of_TS);
TS=(Dailyinput)*0.3033;
Vgs= 0.5*TS*Dailyinput*0.158;
Vh=Vgs;
%% Kinetic Model
% kinetic coefficient
k = 2.7*10^-6 ;
% mass flow rate in (kg/day)
dAdtin = 0 ;
% masss flow rate out
dAdtout = 0 ;
% these are molar masses of each element
mm_carbon = 12.0107 ;
mm_hydrogen = 1.0079 ;
mm_oxygen = 15.999 ;
mm_nitrogen = 14.0067 ;
mm_sulphur = 32.065;
% For C_n H_a O_b N_c S_d + H20 => CO2 + CH4 + H2S+ NH3 + H2O
% These constants come from the ultimate analysis
% These constants dictate the coefficients of each term
```

```
nbymass = 0.45405 ;
abymass = 0.07655 ;
bbymass = 0.42915 ;
cbymass = 0.03945 ;
dbymass = 0.004 ;
% to get molar ratios we divide by molar mass
n = nbymass/mm_carbon;
a = abymass/mm_hydrogen;
b = bbymass/mm_oxygen;
c= cbymass/mm_nitrogen;
d= dbymass/mm_sulphur;
% These are the coefficients in front of each component of the reaction.
% C_n H_a O_b N_c S_d + c_1* H20 --> c_2*CO2 + c_3*CH4+c_4*NH3 + c_5*H2S +
% c_6*H2O
c_1 = n - a/4 -b/2+(3/4)*c+d/2;
c_2 = n/2 -a/8 + b/4+(3/8)*c+d/4;
c_3 = n/2 + a/8 - b/4-(3/8)*c-d/4;
c_4 = c;
c_5 = d;
%c_6 is 7.5% by mass of the methane gas
c_6 = (0.075*c_3*(mm_carbon + 4*mm_hydrogen))/( 2*mm_hydrogen + mm_oxygen) ;

% These are the molar masses of each component
mm_A = mm_carbon*n + mm_hydrogen*a + mm_oxygen*b+ mm_nitrogen*c+
mm_sulphur*d;
mm_B = 2*mm_hydrogen + mm_oxygen ;
mm_C = mm_carbon + 2*mm_oxygen ;
mm_D = mm_carbon + 4*mm_hydrogen ;
mm_E = mm_nitrogen + 3*mm_hydrogen;
mm_F = 2*mm_hydrogen+mm_sulphur;
mm_G = 2*mm_hydrogen + mm_oxygen ;
% These are the masses of each component per mol of food waste
m_A = mm_A;
m_B = c_1*mm_B;
```

```
m_C = c_2*mm_C;
m_D = c_3*mm_D;
m_E = c_4*mm_E;
m_F = c_5*mm_F;
m_G = c_6*mm_G ;
ratio = m_C/(m_C + m_D + m_E + m_F + m_G);
% Initial conditions, mass in Kg, digester capacity in m3, volume of reaction in m3
mass_of_FoodWaste = Dailyinput;
mass_of_water = water_required;
density_of_FoodWaste = 1120;
density_of_water = 1000;
volume_of_reaction = (mass_of_FoodWaste/density_of_FoodWaste +
mass_of_water/density_of_water);
digester_capacity=(Total_influent_required*RT)/(0.8);
Ahat_0 = mass_of_FoodWaste/mm_A/digester_capacity ;
Bhat_0 = mass_of_water/mm_B/digester_capacity ;
Chat_0 = 0;
Dhat_0 = 0;
Ehat_0 = 0;
Fhat_0 = 0;
Ghat_0 = 0;
dAhatdt_0 = -k*Ahat_0*(Bhat_0^(c_1)) ;
dBhatdt_0 = -k*Ahat_0*(Bhat_0^(c_1))*c_1 ;
dChatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_2 ;
dDhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_3 ;
dEhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_4 ;
dFhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_5 ;
dGhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_6 ;
%% Can iterate this process for very small steps of time to approximate the
% new concentration of each component of the reaction
% Concentration of each component put into a row vector
tfinal = RT*24*60*60 ;    % retention time : RT
t = (1:tfinal) ;
Ahat = zeros(1,tfinal) ;
```

```
Bhat = zeros(1,tfinal) ;
Chat = zeros(1,tfinal) ;
Dhat = zeros(1,tfinal) ;
Ehat = zeros(1,tfinal) ;
Fhat = zeros(1,tfinal) ;
Ghat = zeros(1,tfinal) ;
% Rate of concentration of each component put into a row vector
dAhatdt = zeros(1,tfinal) ;
dBhatdt = zeros(1,tfinal) ;
dChatdt = zeros(1,tfinal) ;
dDhatdt = zeros(1,tfinal) ;
dEhatdt = zeros(1,tfinal) ;
dFhatdt = zeros(1,tfinal) ;
dGhatdt = zeros(1,tfinal) ;
% initial conditions put into the first index of the vectors
Ahat(1) = Ahat_0 ;
Bhat(1) = Bhat_0 ;
Chat(1) = Chat_0 ;
Dhat(1) = Dhat_0 ;
Ehat(1) = Ehat_0 ;
Fhat(1) = Fhat_0 ;
Ghat(1) = Ghat_0 ;
dAhatdt(1) = dAhatdt_0 ;
dBhatdt(1) = dBhatdt_0 ;
dChatdt(1) = dChatdt_0 ;
dDhatdt(1) = dDhatdt_0 ;
dEhatdt(1) = dEhatdt_0 ;
dFhatdt(1) = dFhatdt_0 ;
dGhatdt(1) = dGhatdt_0 ;
% simulation run for small time steps to give concentration over time
for i = 2:tfinal
Ahat(i) = Ahat(i-1) + dAhatdt(i-1) ;
Bhat(i) = Bhat(i-1) + dBhatdt(i-1) ;
Chat(i) = Chat(i-1) + dChatdt(i-1) ;
```

```
Dhat(i) = Dhat(i-1) + dDhatdt(i-1) ;
Ehat(i) = Ehat(i-1) + dEhatdt(i-1) ;
Fhat(i) = Fhat(i-1) + dFhatdt(i-1) ;
Ghat(i) = Ghat(i-1) + dGhatdt(i-1) ;
dAhatdt(i) = -k*Ahat(i)*(Bhat(i)^(c_1)) ;
dBhatdt(i) = -k*Ahat(i)*(Bhat(i)^(c_1))*c_1 ;
dChatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_2 ;
dDhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_3 ;
dEhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_4 ;
dFhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_5 ;
dGhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_6 ;
end
% mols converted to mass of gas produced
mols_of_c = Chat*digester_capacity ;
mols_of_d = Dhat*digester_capacity ;
mols_of_e = Ehat*digester_capacity ;
mols_of_f = Fhat*digester_capacity ;
mols_of_g = Ghat*digester_capacity ;
mass_of_CO2 = mols_of_c*mm_C ;
mass_of_CH4 = mols_of_d*mm_D ;
mass_of_NH3 = mols_of_e*mm_E ;
mass_of_H2S = mols_of_f*mm_F ;
mass_of_H2O = mols_of_g*mm_G ;
% fitting factor used to adjust model to experiment
fitting_factor = .0085 ;
mass_of_CO2_fitted = mass_of_CO2*fitting_factor ;
mass_of_CH4_fitted = mass_of_CH4*fitting_factor ;
mass_of_NH3_fitted = mass_of_NH3*fitting_factor ;
mass_of_H2S_fitted = mass_of_H2S*fitting_factor ;
mass_of_H2O_fitted = mass_of_H2O*fitting_factor ;
%volume of constituent gas
t_fitted = t/(60*60*24) ;
pressure_Pa = 101325 ;
T = 311 ; %K ;
```

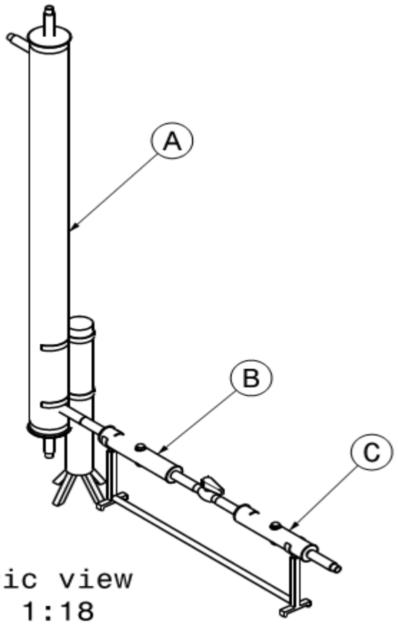
```
R = 8.314 ; %J/mol/K
R_H2O = 461.52 ; %J/KgK H2O specific gas constant of H2O where water vapor is
considered sa an ideal gas.
Volume_of_CO2 = (mass_of_CO2_fitted*R*T)/(pressure_Pa*mm_C)*10000;
Volume_of_CH4 = (mass_of_CH4_fitted*R*T)/(pressure_Pa*mm_D)*10000;
Volume_of_NH3 = (mass_of_NH3_fitted*R*T)/(pressure_Pa*mm_E)*10000;
Volume_of_H2S = (mass_of_H2S_fitted*R*T)/(pressure_Pa*mm_F)*10000;
Volume_of_H2O = (mass_of_H2O_fitted*R*T)/(pressure_Pa*mm_G)*10000;
Vol_Biogas =(Volume_of_CO2+Volume_of_CH4+Volume_of_NH3+
Volume_of_H2S+Volume_of_H2O);
Volume_of_CO2 = (Vol_Biogas*0.30);
Volume_of_CH4 = (Vol_Biogas*0.65);
Volume_of_NH3 = (Vol_Biogas*0.001);
Volume_of_H2S = (Vol_Biogas*0.01);
Volume_of_H2O = (Vol_Biogas*0.04);
% density of consituent gases
density_of_CO2 = 1.824;
density_of_CH4 = 0.668;
density_of_NH3 = 0.717;
density_of_H2S = 1.434;
%mass of constuent gas
mass_of_CO2 = Volume_of_CO2*density_of_CO2;
mass_of_CH4 = Volume_of_CH4*density_of_CH4;
mass_of_NH3 = Volume_of_NH3*density_of_NH3;
mass_of_H2S = Volume_of_H2S*density_of_H2S;
mass_of_H2O = (pressure_Pa*Volume_of_H2O)/(R_H2O*T*1000);
Vol_Biogas =(Volume_of_CO2+Volume_of_CH4+Volume_of_NH3+
Volume_of_H2S+Volume_of_H2O);
%mass of adsorbent and absorbent
mass_of_NaOH_solution = 3.5*mass_of_CO2;% mass of absorbent solution
mass_of_NaOH = 0.1*mass_of_NaOH_solution;
mass_of_Calcium_Hdroxide_solution = 3.78*mass_of_CO2; %mass of absorbent solution
mass_of_Calcium_Hydroxide = 0.1*mass_of_Calcium_Hdroxide_solution;
mass_of_activated_carbon = 2.19*mass_of_H2S;
```

```
mass_of_steel_wool = 3.94*mass_of_H2S;
mass_of_Biogas =
mass_of_CO2+mass_of_CH4+mass_of_NH3+mass_of_H2S+mass_of_H2O;
mass_of_H2O = 0.04*mass_of_Biogas;
mass_of_sodium_sulfate = 2.87*mass_of_H2O;
mass_of_silica_gel = 2.36*mass_of_H2O;
plot(t_fitted , mass_of_CH4,'b', t_fitted, mass_of_CO2, 'r', t_fitted, mass_of_H2S,'m',
t_fitted,mass_of_H2O,'b', t_fitted,mass_of_NaOH,'r', t_fitted,
mass_of_Calcium_Hydroxide,'g', t_fitted,
mass_of_activated_carbon,'k',t_fitted,mass_of_steel_wool,'g',t_fitted, mass_of_silica_gel,'m',
t_fitted, mass_of_sodium_sulfate,'y','LineWidth',1.6)
legend('CH4 model', 'CO2 model', 'H2S model','H2O model','NaOH Model','Calcium
Hydroxide model','activated carbon model','steel wool model','silica gel model','sodium
sulfate model')
set(gca,'FontSize',12,'FontWeight','bold','linewidth',1.5)
ylabel('mass of gases and chemicals (kg)','FontSize',12,'FontWeight', 'bold')
xlabel('time(days)','FontSize',12,'FontWeight', 'bold')
calorific_value_of_biomethane=50*10^6;
biomethane_conversion_efficiency=0.38;
biogas_produced=0.09*Dailyinput;
biomethane = biogas_produced;
fuel_consumption = biomethane/9; % engine run for 9hour
max_mass_fuel_consumption=max(fuel_consumption);
Power_available=calorific_value_of_biomethane/3600*fuel_consumption;
max_Power_available=max(Power_available);
rated_power_generated= Power_available*biomethane_conversion_efficiency;
max_rated_power_generated = max(rated_power_generated)
fprintf('rated_power_generated in w\n')
fprintf('During the process %w w of rated power is generated\n',sum(Power_available))
disp('==========================================================')
disp('----------------------------------------------------------------------------------------------------')
```

>> **Result from mat lab**

```
Insert Daily input in Kg? 115
Insert Retention Time_No of days? 30
Insert Concentration_of_TS? 0.09
```

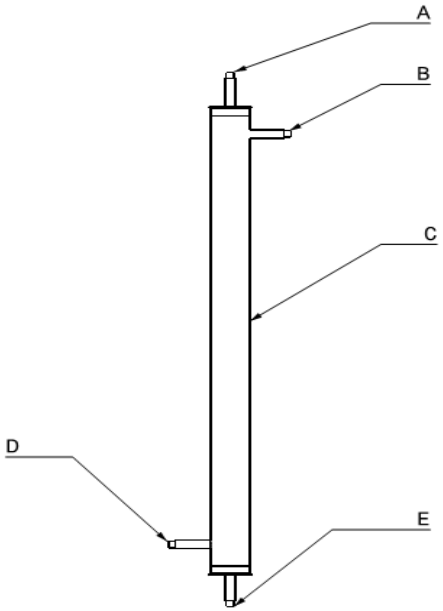
- ✓ max_rated_power_generated = 6.0694e+03 rated power generated in w during the process



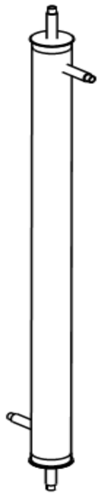
Isometric view
Scale: 1:18

DESIGNED BY: TAMRAT MOGES		THE OVERALL SYSTEMES OF BIOGAS UPGRADING	
CHECKED BY: DR. ING. WONDWOSSEN BOGALE			
DATE 21-Nov-2018			
SCALE 1:18	DRAWING UNIT (mm)	DRAWING NUMBER PART 1	

I	_
H	_
G	_
F	_
E	_
D	_
C	H_2S SCRUBBER UNIT
B	H_2O SCRUBBER UNIT
A	CO_2 SCRUBBER UNIT



Front view
Scale: 1:18



Isometric view
Scale: 1:18

Top view
Scale: 1:18

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE
19-Nov-2018

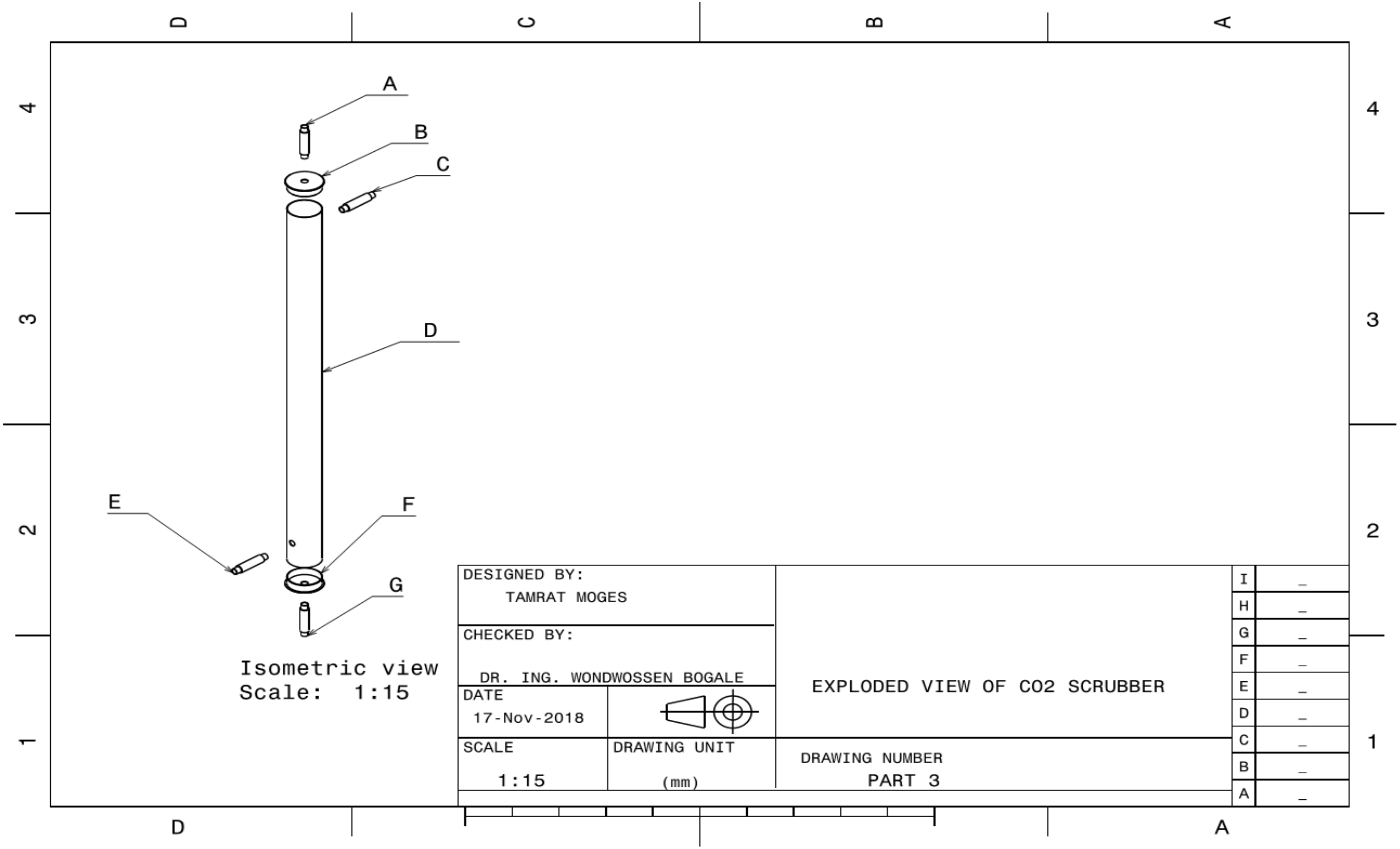
CO_2 GAS SCRUBBER UNIT

SCALE
1:18

DRAWING UNIT
(mm)

DRAWING NUMBER
PART 2

I	_
H	_
G	_
F	_
E	OUT LET PORT CO2 ENRICH SOLUTION
D	BIOGAS IN LET PORT
C	CO2 SCRUBBER COLUMN
B	IN LET PORT SCRUBBER SOLUTION
A	OUT LET PORT OF METHANE ENRICH GAS



Isometric view
Scale: 1:15

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE
17-Nov-2018

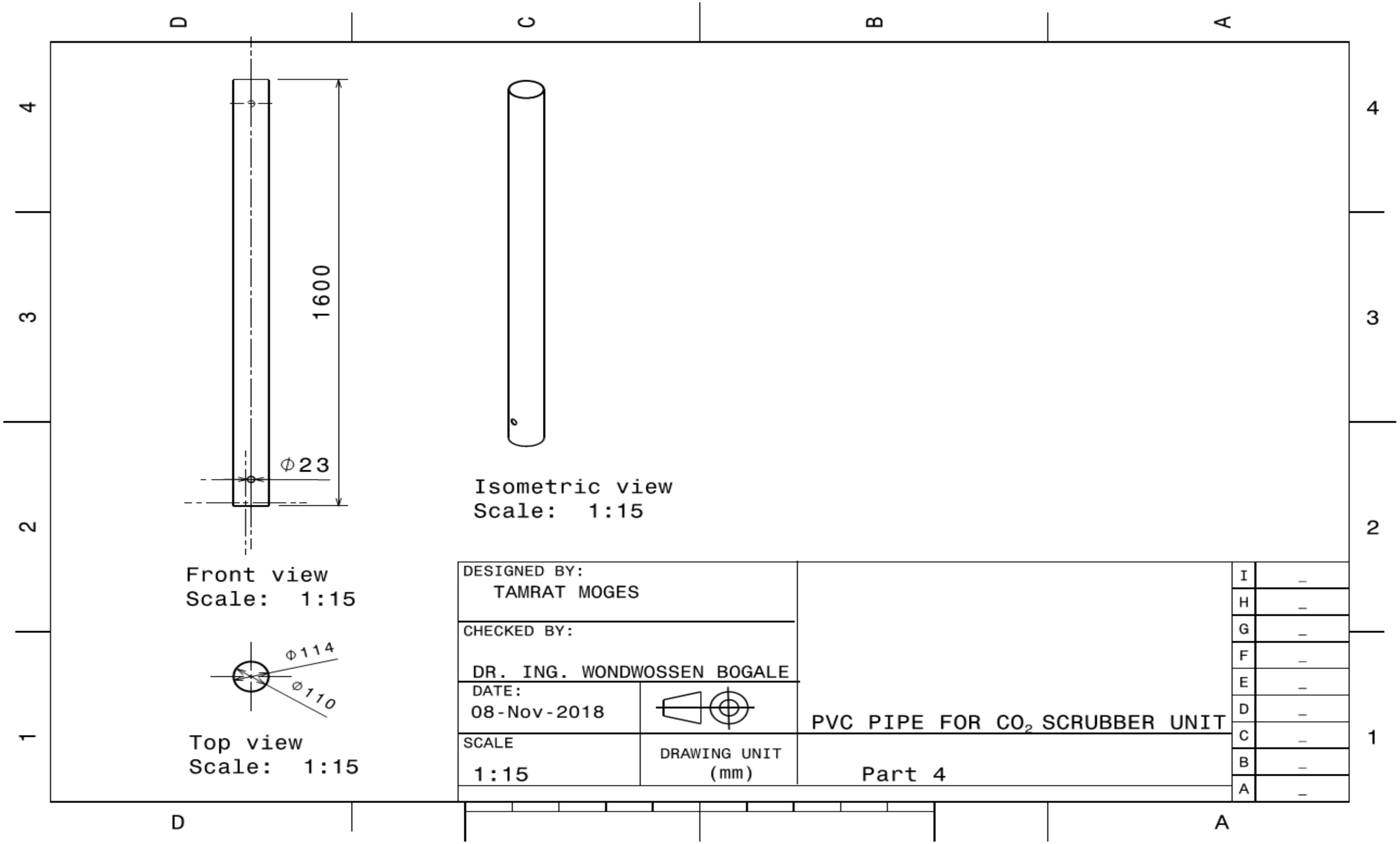
EXPLODED VIEW OF CO2 SCRUBBER

SCALE
1:15

DRAWING UNIT
(mm)

DRAWING NUMBER
PART 3

I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE:
08-Nov-2018

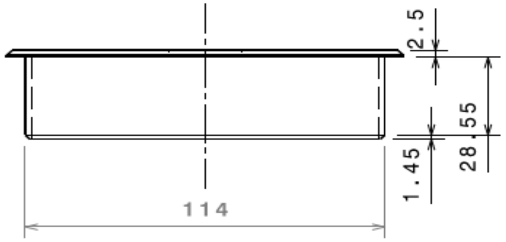
SCALE
1:15

DRAWING UNIT
(mm)

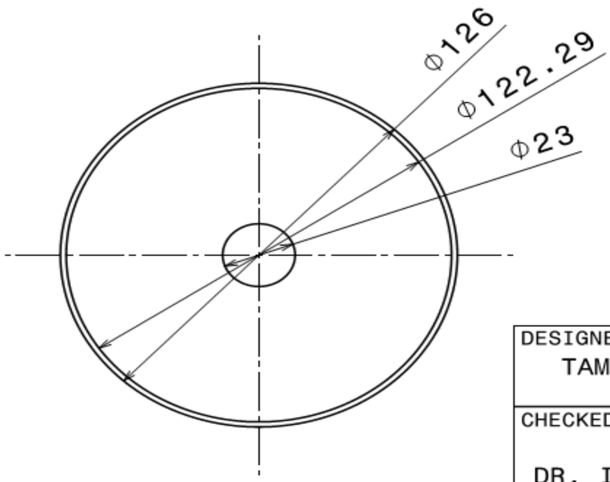
PVC PIPE FOR CO_2 SCRUBBER UNIT

Part 4

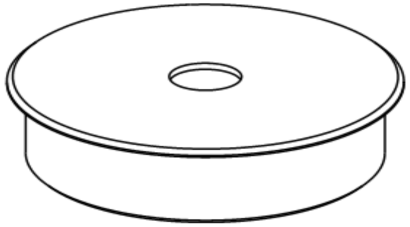
I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



Front view
Scale: 1:2



Top view
Scale: 1:2



Isometric view
Scale: 1:2

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE:
08-Nov-2018

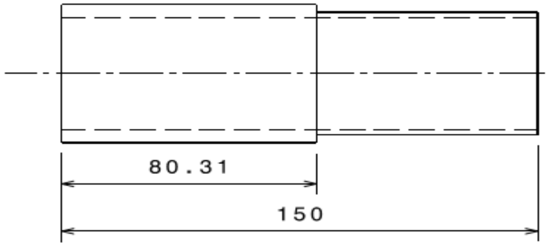
PVC CUP FOR CO_2 SCRUBBER UNIT

SCALE
1:1

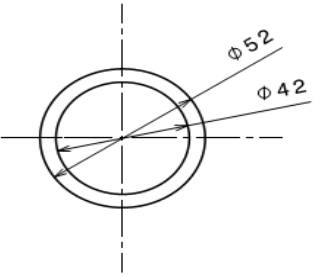
DRAWING UNIT
(mm)

DRAWING NUMBER
Part 5

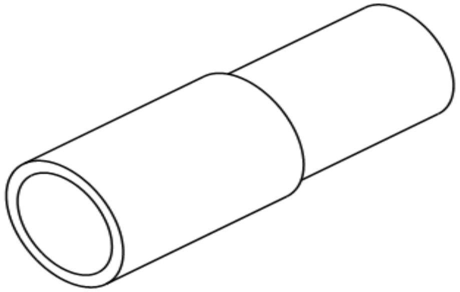
I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



Front view
Scale: 1:2



Left view
Scale: 1:2



Isometric view
Scale: 1:2

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE
08-Nov-2018

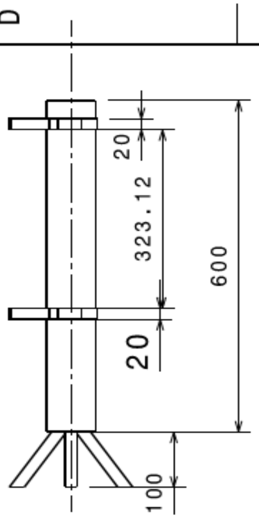
PPR PORT FOR BIOGAS
UPGRADING

SCALE
1:2

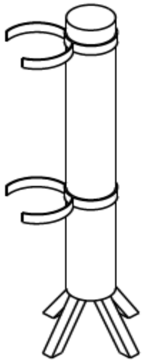
DRAWING UNIT
(mm)

DRAWING NUMBER
Part 6

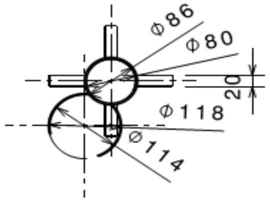
I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



Front view
Scale: 1:10



Isometric view
Scale: 1:10



Top view
Scale: 1:10

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE
22-Nov-2018

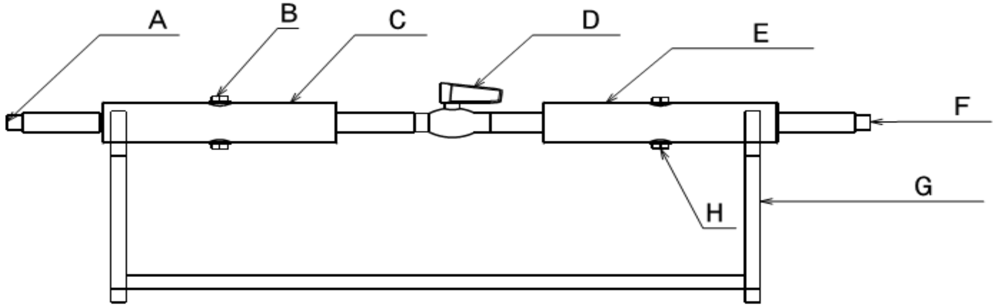
SUPPORT OF CO_2 SCRUBBER

SCALE
1:10

DRAWING UNIT
(mm)

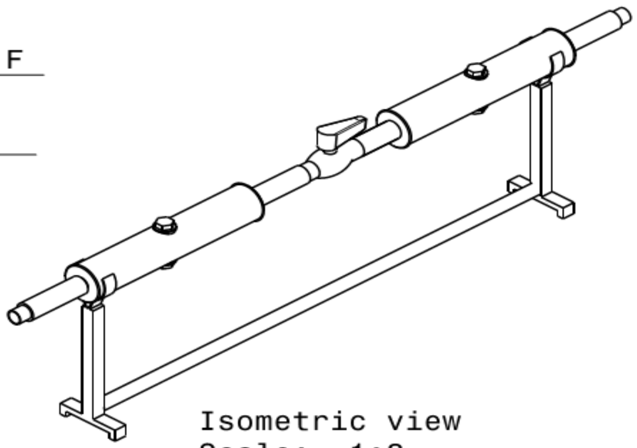
DRAWING NUMBER
PART 7

I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



Front view
Scale: 1:8

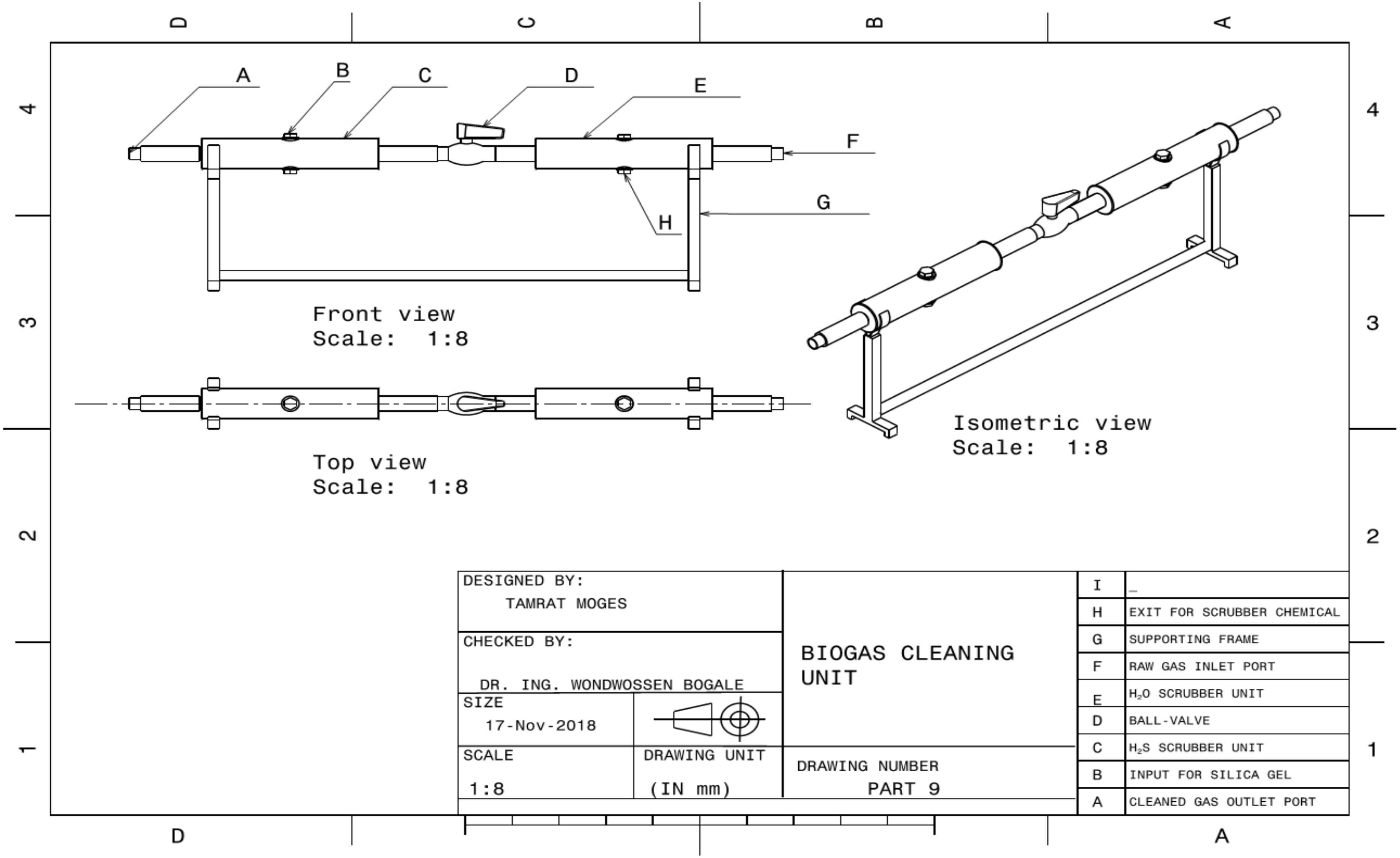
Top view
Scale: 1:8



Isometric view
Scale: 1:8

DESIGNED BY: TAMRAT MOGES		BIOGAS CLEANING UNIT
CHECKED BY: DR. ING. WONDWOSSEN BOGALE		
SIZE 17-Nov-2018		
SCALE 1:8	DRAWING UNIT (IN mm)	DRAWING NUMBER PART 8

I	_
H	EXIT FOR SCRUBBER CHEMICAL
G	SUPPORTING FRAME
F	RAW GAS INLET PORT
E	H_2O SCRUBBER UNIT
D	BALL-VALVE
C	H_2S SCRUBBER UNIT
B	INPUT FOR SILICA GEL
A	CLEANED GAS OUTLET PORT



DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

SIZE
17-Nov-2018

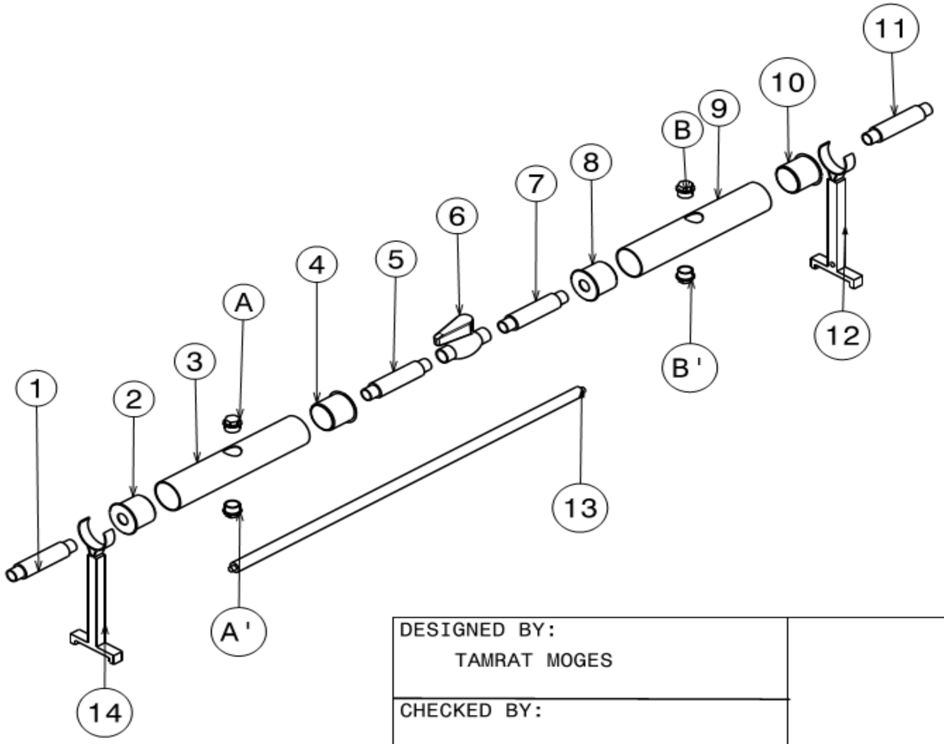
SCALE
1:8

DRAWING UNIT
(IN mm)

BIOGAS CLEANING UNIT

DRAWING NUMBER
PART 9

I	_
H	EXIT FOR SCRUBBER CHEMICAL
G	SUPPORTING FRAME
F	RAW GAS INLET PORT
E	H_2O SCRUBBER UNIT
D	BALL-VALVE
C	H_2S SCRUBBER UNIT
B	INPUT FOR SILICA GEL
A	CLEANED GAS OUTLET PORT



Isometric view
Scale: 1:10

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE
21-Nov-2018

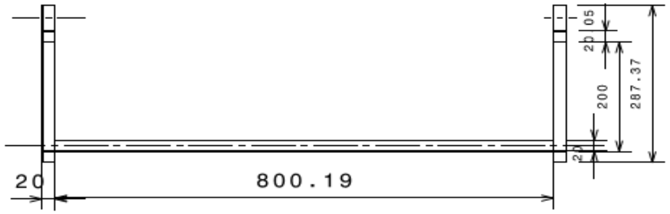
EXPLODED VIEW OF BIOGAS
CLEANING UNIT

SCALE
1:10

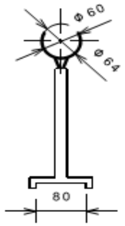
DRAWING UNIT
(mm)

DRAWING NUMBER
PART 10

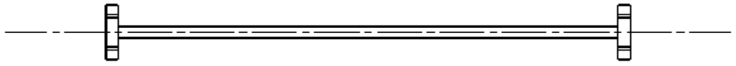
I	_
H	_
13	CONNECTOR ROD
12,14	SUPPORTING FRAME LEGS
6	BALLVALVE
3,9	PPR PIPE
A,A',B,B'	PPR NUT
2,4,8,10	PPR PIPE CUPS
1, 5,7,11	CONECTER PORTS



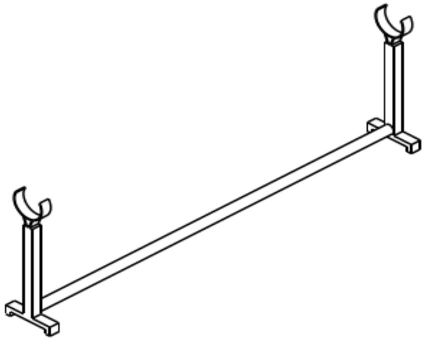
Front view
Scale: 1:10



Left view
Scale: 1:10



Top view
Scale: 1:10



Isometric view
Scale: 1:10

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE
19-Nov-2018

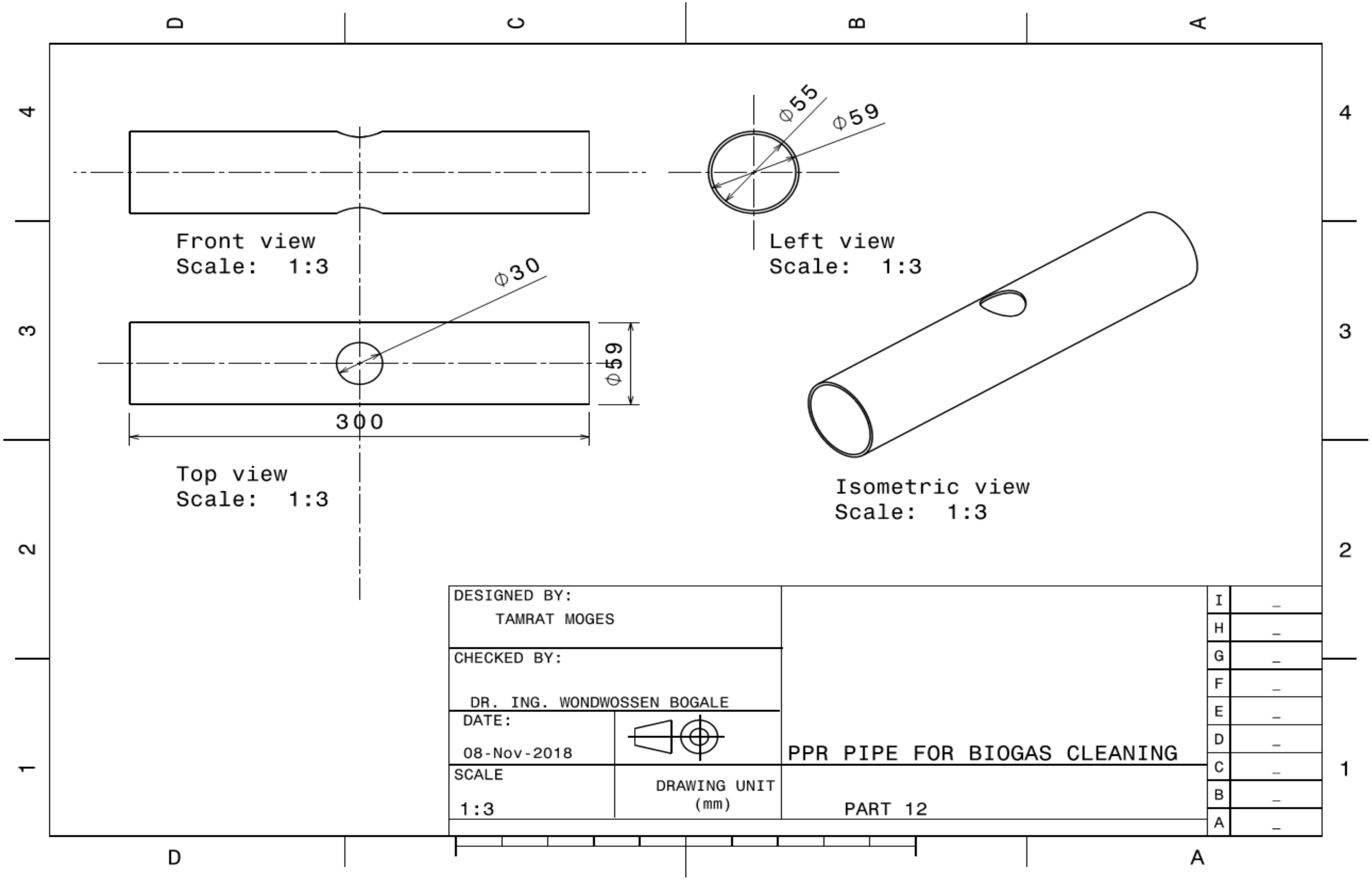
SUPPORTING FRAME FOR BIOGAS CLEANING UNIT

SCALE
1:10

RDAWING UNIT
(mm)

DRAWING NUMBER
PART 11

I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

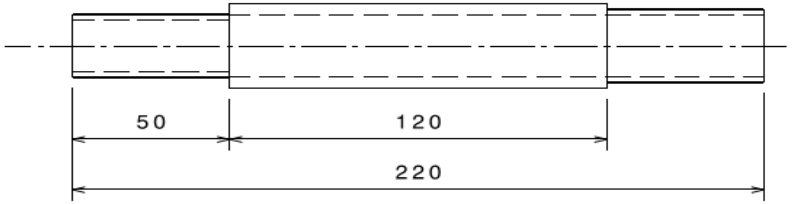
DATE:
08-Nov-2018

SCALE
1:3

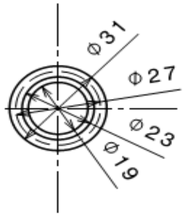
DRAWING UNIT
(mm)

PPR PIPE FOR BIOGAS CLEANING

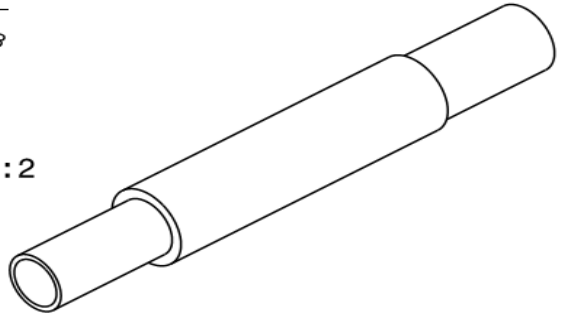
PART 12



Front view
Scale: 1:2



Left view
Scale: 1:2



Isometric view
Scale: 1:2

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE:
08-Nov-2018

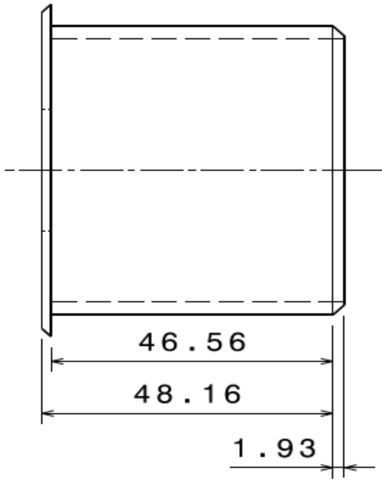
SCALE
1:2

DRAWING UNIT
(mm)

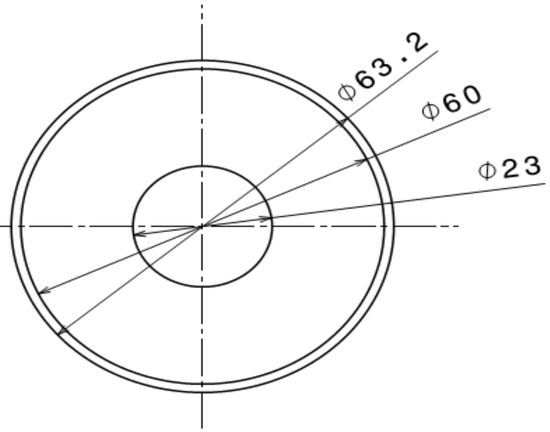
PPR PORT FOR BIOGAS CLEANING UNIT

DRAWING NUMBER
PART 13

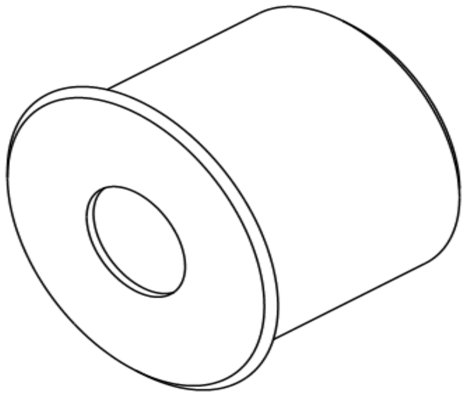
I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



Front view
Scale: 1:1



Left view
Scale: 1:1



Isometric view
Scale: 1:1

DESIGNED BY:
TAMRAT MOGES

CHECKED BY:
DR. ING. WONDWOSSEN BOGALE

DATE:
08-Nov-2018

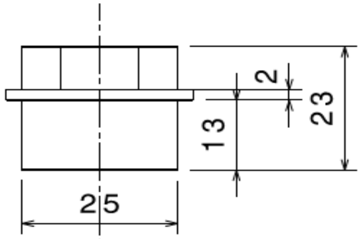
PVC CUP

SCALE
1:1

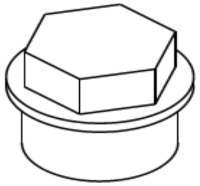
DRAWING UNIT
(mm)

PART 14

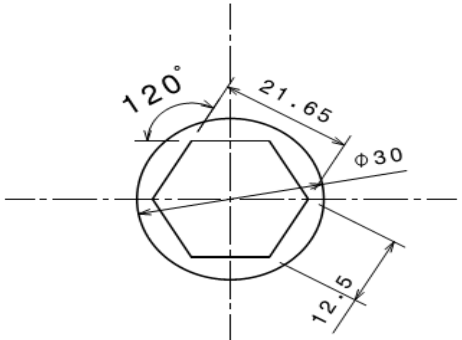
I	_
H	_
G	_
F	_
E	_
D	_
C	_
B	_
A	_



Front view
Scale: 1:1



Isometric view
Scale: 1:1



Top view
Scale: 1:1

DESIGNED BY: TAMRAT MOGES		NUT COVER FOR INLET AND OUTLET OF SCRUBBER CHEMICAL	I _ H _ G _ F _ E _ D _ C _ B _ A _
CHECKED BY: DR. ING. WONDWOSSEN BOGALE			
Date 19-Nov-2018			
SCALE 1:1	DRAWING UNIT (mm)	DRAWING NUMBER PART 15	