Pan African University
Institute of Water
and Energy Sciences

جامعة أبو بكر بلقايد
UNIVERSITÉ DE TLEMCEN

PAN-AFRICAN UNIVERSITY
INSTITUTE OF WATER AND ENERGY SCIENCES
(Including climate change)

MASTER DISSERTATION

Submitted in partial fulfillment of the requirements for the Master degree in

ENERGY ENGINEERING

BY

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Design of a Co-Digestion biogas plant for households: A study case of Rwanda, Gicumbi District.

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Academic year: 2018-2019

DEDICATION

This Master thesis is highly dedicated to the Almighty God

DECLARATION

I, Jean Marie Vianney HABURUKUNDO, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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CERTIFICATION

This is to certify that the master's thesis entitled **"Design of a Co-Digestion biogas plant for households**: **A study case of Rwanda, Gicumbi District"** is a record of the original bona fide work done by Jean Marie Vianney HABURUKUNDO *in partial fulfillment of the requirement for the award of Master of Science Degree in Energy Engineering track at Pan African University Institute of Water and Energy Sciences (Including climate science)- PAUWES during the Academic Year 2018-2019.*

Signature: **Date: 22nd, September 2019**

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ABSTRACT

Energy is a backbone for economic development globally as well as in Rwanda. Low access to the reliable energy resources for Rwandans is a crucial challenge that needs more efforts to be resolved. Households in Rwanda are the major consumers of the energy with 91% of primary energy consumption and 51% of electricity consumption, whereby 99 % of the energy consumed in households come from biomass. Several researches, for alternatives and modern energy use for environmental sustainability, have been done. Among them biogas technology, which was introduced in the current energy mix of Rwanda with the target of providing clean and environmental friendly energy alternatives for Rwandans.

At first, NDBP was developed by the Government, in collaboration with SNV, with the intention of deploying biogas digesters around the country for household as well as institutional levels. Among the challenges encountered by this program were high upfront cost to initiate a biogas digester deployment and low access to the feedstock resources mainly. This program was required to have at least two heads cattle per house in order to launch a biogas plant. In this regards this thesis work was intended at designing a co-digestion biogas plant that would use human faeces along with caw dung to generate biogas for households in Rwanda. This work is one of the solutions for feedstock materials, and biogas plant. In study a centralized digester plant for 5 households was looked at in order facilitate the financial affordability of the plant. The specific home activities considered during the design of biogas plant in the study were direct cooking and heating water through biogas stove. This study was carried out in Gicumbi District, Northern Province of Rwanda as the pilot study.

A biogas plant of 30.82 m^3 volume of size, with 25.6m^3 of digester volume and 5.22 m^3 volume of gas holder is required in order to provide 2.9 m^3 of biogas per day, that is equivalent to the daily energy needs per each of 5 households. The use of this co-digestion biogas plant would save 2.1tones of charcoal for 5 households annually. This could help to preserve the environment through reduced forest cutting. The financial analysis found that a (Bricks/concretes) biogas plant, in the study, needs RWF 4,000,000 or USD 4444 as initial investment, with annual income of RWF1,221,300 or USD1188 in terms of saving from buying charcoal and due to the selling of bio-slurry as fertilizers.

RÉSUMÉ

L'énergie est un pilier du développement économique au niveau mondial et au Rwanda. Le faible accès des Rwandais à des ressources énergétiques fiables est un défi crucial qui nécessite des efforts supplémentaires pour être résolu. Les ménages rwandais sont les principaux consommateurs d'énergie avec 91% de la consommation d'énergie primaire et 51% de la consommation d'électricité, 99% de l'énergie consommée par les ménages provenant de la biomasse. Plusieurs recherches sur les alternatives et l'utilisation moderne de l'énergie pour la durabilité de l'environnement ont été effectuées. Parmi eux, la technologie du biogaz, qui a été introduite dans le mix énergétique actuel du Rwanda dans le but de fournir des alternatives énergétiques propres et respectueuses de l'environnement aux Rwandais.

Au départ, le gouvernement a mis au point le programme NDBP, en collaboration avec la SNV, dans le but de déployer des digesteurs de biogaz dans tout le pays, tant au niveau des ménages que des institutions. Parmi les défis rencontrés par ce programme, il y avait les coûts initiaux élevés pour lancer le déploiement d'un digesteur de biogaz et le faible accès aux ressources en matières premières principalement. Ce programme devait comporter au moins deux vaches par maison pour pouvoir lancer une usine de production de biogaz. À cet égard, cet travail de thèse visait à concevoir une installation de biogaz à digestion conjointe qui utiliserait des matières fécales humaines ainsi que de la bouse de vache pour générer du biogaz pour les ménages rwandais.

Cet travail constitue l'une des solutions pour les matières premières et l'usine de biogaz. Dans cette étude, une installation de digestion centralisée pour 5 ménages a été examinée afin de faciliter l'accessibilité financière de l'usine. Les activités spécifiques à la maison prises en compte lors de la conception de l'usine de production de biogaz dans l'étude étaient la cuisson directe et le chauffage de l'eau au moyen d'un réchaud à biogaz. Cette étude a été réalisée dans le District de Gicumbi, Province du Nord du Rwanda, à titre d'étude pilote. Une installation de production de biogaz de 30,82 m^3 de volume, avec 25,6 m^3 de digesteur et 5,22 m^3 de réservoir de gaz, est nécessaire pour fournir 2,9 m^3 de biogaz par jour, ce qui correspond aux besoins énergétiques quotidiens de chacun des cinq ménages. L'utilisation de cette installation de biogaz par digestion conjointe permettrait d'économiser 2,1 tonnes de charbon de bois pour 5 ménages par an. Cela pourrait aider à préserver l'environnement grâce à une réduction des coupes forestières.

L’analyse financière a révélé qu’une installation de production de biogaz (briques / bétons) nécessitait dans l’étude un investissement initial de 4 000 000 FRW, soit 4 444 USD, avec un revenu annuel de 1 221 300 FRF, soit de 1 118 USD en termes d’économies résultant de la vente de charbon et suspension biologique en tant qu'engrais.

ACKNOWLEDGEMENTS

First of all, I would like to give thanks to the Almighty God who has walked with me throughout this journey and before. Without the constant guidance and protection of the Lord, this master thesis would be a dream.

Secondly, my special thanks are addressed to African Union Commission and GIZ for giving the opportunity and providing me all the requirements in terms of financial support to accomplish my master’s studies. I thank them so much.

Thirdly, I would like to express my sincere appreciation to my supervisor Dr. Paul CHISALE for review of this thesis in detail and his important feedback. This Professor has patiently encouraged and guided me to do the best work throughout each stage.

Finally, I send many thanks to my family for their invaluable care, encouragement and support throughout my study. Because this work would not have been possible without the love and support of my parents, brothers and sisters, immediate family and friends who have always encouraged and believed in me, in all my endeavors. In fact, I received great inspiration from their love and friendship, even from thousands of miles away.

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List of abbreviations

AD: Anaerobic Digestion

CEMERWA: Cement du Rwanda

EWSA: Energy and Water Sanitation Agency

EUEI: European Union Energy Initiative

EU: European Union

EAC: East African Community

EDPRS: Economic Development and Poverty Reduction Strategy

GHG: Green House Gas

GDP: Gross Domestic Product

HRT: Hydraulic Retention Time

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

ICRC: International Committee of the Red Cross

MINICOFIN: Ministry of Finance and Economic Planning

MINIFRA: Ministry of Infrastructure

NPK: Nitrogen Phosphorus Potassium

NISR: National Institute of Statistics of Rwanda
NDBP: National Domestic Biogas Program

OXFAM: Oxford Committee for Famine Relief

OLR: Organic Loading Rate

PVGIS: Photovoltaic Geography Information System

Ppm: Particles per mole

REMA: Rwanda Environmental Management Authority

REG: Rwanda Energy Group

SNV: Stichting Nederlandse Vrijwilligers (Netherlands Development Organization)

TERI: Tata Energy Research Institution

UR-CST: University of Rwanda College of Science and Technology

VFA: Volatile Fatty Acid

CHAPTER ONE: INTRODUCTION

1.0. Thesis overview and outlines

Energy is a key factor for most of human activities accomplishment, either in directly way as fuel or indirectly way for power, light and mobility provision. Combination of Energy and technology multiplied human abilities thereby playing a crucial role in pre- industrial as well as in post-industrial, then to the current information technology societies. Referred to Emmanuel, B. et al., (2013), poor access to the reliable and affordable modern energy services is a crucial challenge for economic and social development, with which the global disproportion in energy resources and demand acts as a constraint to sustain the economic development for future. Furthermore, depletion of petroleum oil and gas reserves in developed countries coupled with high global energy demand due to the population growth and massive industrialization, are creating a future worries for global energy security. According to IEA (2017), total global energy consumption reached 3635 Mtoe in 2015 whereby renewables share accounted only 19.3%, and world primary energy consumption increased by 2.2% in 2017 (Petroleum, 2018). Fossil fuels are the most dominant in the global energy portfolio and drive the economic systems in both developing and developed countries, these have intensive environmental hazardous (Emmanuel, B. et al., 2013). Increased trend in the energy demand along with manner of energy harvesting and use, in which fossil fuels are dominant, are harming to the environment and results into the climate change due to the greenhouse gas (GHG) emissions mainly carbon dioxide (CO_2) from burning fossil fuels (Surendra et al., 2014).

Global penetration of renewable alternatives along with more energy efficient technologies may be a win-win option to meet global energy needs as well as sustainable development for better future (Mirchi, A. et al.,2012). Rapid deployment of Renewables like wind, solar, geothermal, hydro, maritime, and modern biomass such as biogas are crucial. According to Abbas.T, et al., (2012), biogas has a huge potential to drive economic development sustainably.

Biogas technology offers substantial opportunities for employment through the value chain from the production and harvesting of feed stock, to the production, construction and /or installation and maintenance of the biogas digester unit, or the sale of produced biogas. According to IRENA (2017), biogas production and use created 333,000 jobs globally as of 2015, with trend to increase as biogas for cooking and others applications expands. Jobs created due to the biogas deployment include 145000 in Chine, 85000 in India, 45000 in Germany, 19000 in Europe (excluding Germany),15000 in Bangladesh, 7000 in United states and 15000 in other countries. In addition, biogas technology is dynamic in hygienic provision, deforestation reduction and environmental protection by capturing and use of Methane from waste disposal, which is a dangerous greenhouse gas for global warming. The annual benefits of an average household biogas in Nepal cover 2 tons of firewood, 1 ton of agricultural residues, 250 kg of dried dung,70 kg of kerosene, and provides chemical fertilizers with 39 kg of nitrogen, 19 kg of phosphorous, and 39 kg of potassium, in addition to the health benefits through reduced indoor air pollution (Abbas.T, et al., 2012).

Rwanda has been one of the fastest growing economy in East Africa in the last decade. Among others, Rwanda had fast growing electricity accessibility rate of 8% in 2008 that stood at 23% as of 2017 (Ituze.G., et al.,2017) and 30 % in 2018. Currently, Hydropower remains the major source of electricity, followed by solar which has high potential up to the maximum irradiance of 5.8 kWh/ m^2/day. Biomass, at 85%, is the Rwanda's primary energy source. Households consume 91% of the total primary energy mix with 97% of that consumption in households comes from woods and Charcoals. Biogas portion in the primary energy mix consumption (in the households) is less than 1%. however high rate of biomass consumption. This traditional biomass consumption is hazardous to the environment results from the huge forest cutting per year.

In this regard, this thesis work is dedicated to the use of human excreta along with cow dung to generate biogas through anaerobic digestion process. This biogas will serve as cooking fuel in the households. A centralized co-digestion bio-digester plant was designed to supply biogas for direct cooking applications in the rural households, with the pilot study of Gicumbi district in the North province of Rwanda.

1.1. Background

Rwanda is a small land-locked country having 26,338 km^2 of area see figure1, with 12,208,407 of inhabitants (NISR, 2017). It is a country located in Central Africa and whose geographical coordinates lay between $1^o04'$ and $2^o51'$ latitude South and $28^o45'$ and $31^015'$ longitude East (NISR, 2013). Country’s GDP per capita is 748.39 USD (MINICOFIN,2018). Population density of the country is among the highest in Africa with 474.64 person / sq. km (World population review, 2018).

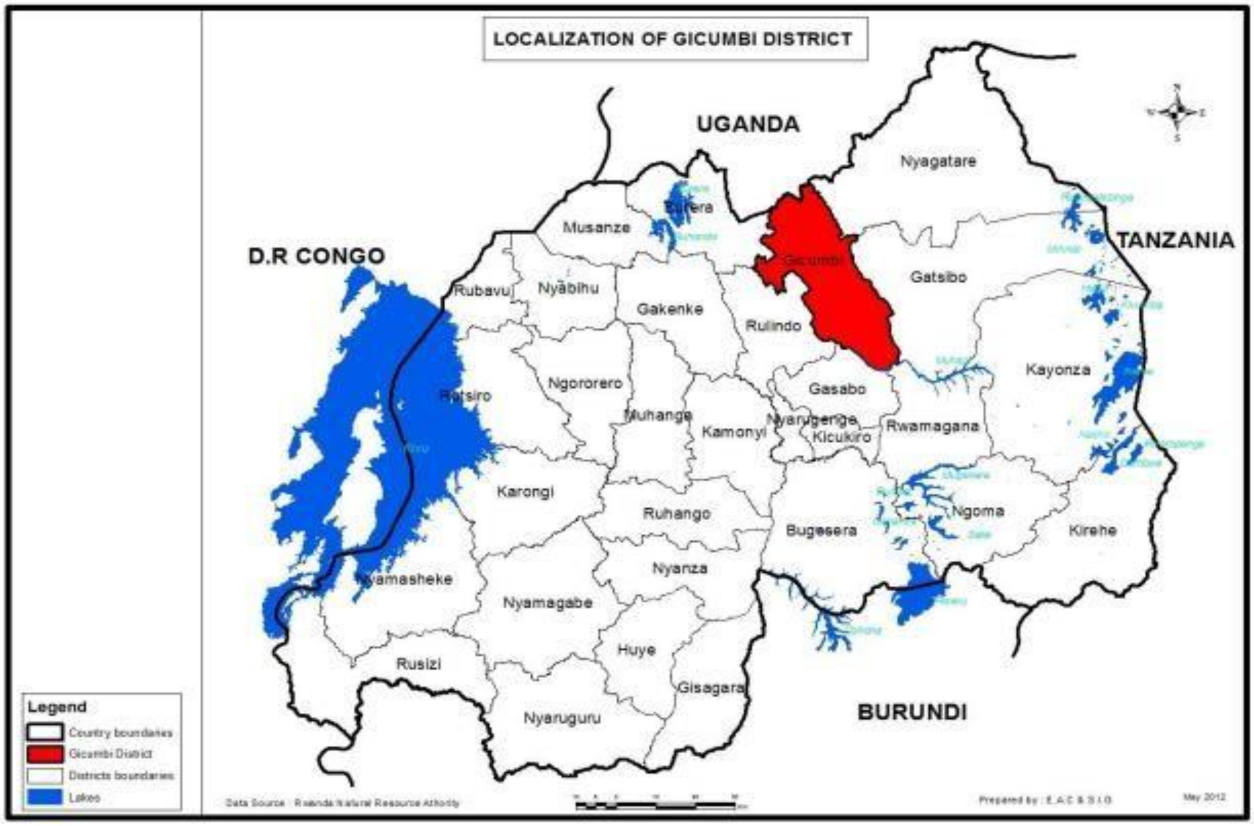


Figure 1. Rwanda Demographic map (Source: Rwanda Natural Resource Authority, 2015)

In Rwanda, like worldwide, energy plays a fundamental role in social and economic development as well as poverty eradication. According to MINIFRA (2016), in Rwanda households are the dominate consumers of primary energy at 91% of total energy mix, followed by the transport 4%, industry 3%, and public services 2%. Households also dominates in electricity consumption with 51% mainly for lighting, followed by industries 32%, public sectors16% and export 1 %. Only for cooking and heating water activities, households rely on biomass (99%), where 86% comes from firewood, 11% from charcoal, 2% from crop wastes; and other fuels account for 1%.

According to Ituze.G., et al., (2017), by 2004, demand of wood fuel in Rwanda was estimated at 18.22 million tons with annual extraction potential of 7.7 million tons corresponding to the country's forests decline rate of 7 %. And as of 2017, wood fuel consumption reached 2.7 million tons per year in both rural and urban residential areas for cooking and heating water. This high dependence on firewood put further pressure on the standing stokes of biomass with about 870,000 tons of wood scarcity as of 2012 (MININFRA, 2015).

Households in Rwanda with access to grid powered-electricity were 30% as of 2017, and 10.7% accessed the off-grid electricity (MININFRA, 2018). This portion indicates that the majority of households are still relying on woods for both cooking and lighting. Currently100% of petroleum related products, in Rwanda, come from the import which makes them expensive and inaccessible for majority of population. Low affordability to petroleum-based fuels and higher reliance on wood as energy source is a long term challenge for economic development of country that was aligned with Vision 2020 (MINICOFIN,2018). As such, diversification and further energy alternatives including National Domestic Biogas Program (NDBP) characterized a progress toward sustainable energy supply and tried to minimize reliance on the firewood for the country.

Biogas technology was incorporated in the current energy mix available in the country due to its various advantages, because it provides reliable gas for cooking, heating, lighting and transportation. Furthermore, bio product from biogas digester called bio-slurry is non-polluting, odorless, rich in nutrients such as Nitrogen, Potassium, and Sodium (NPK) that are useful to crops (Yasar et al., 2017). Also, biogas technology is beneficial compared to other renewables as the system is built in the way that temporarily store gas to be used at different times (Sarah Refai, 2016)**.** Biogas technology helps in waste management, as a tool to mitigate climate change compared to the open land fill waste disposal which in natural way emit methane and carbon dioxide as untreated wastes.

1.2. Problem statement

Rwanda as one of the rapid developing countries in the region with high population density of 474.64 person / sq. km (World population review, 2018). The population growth was estimated at 2.4% by 2018; with low average land possession per capita of 0.25 ha in 2010 projected to be 0.19 ha in 2020 and 0.1 ha by 2050 (REMA,2011). Agriculture plays a major role in economic development where 91% of food consumption is produced locally, 34% of GDP and 70% of national revenue come from agricultural activities (Bizimana, C. et al., 2012& Harding, B., 2009). The Government is introducing the so called modern villages program whereby people are supposed to live in some specific places (literally known as IMIDUGUDU) and leave the rest of land for agriculture mainly in rural areas. Hence, the problem of energy deficient in those particular villages mainly for cooking and heating water arises, as the lifestyle in those villages look like that in urban areas but with different financial capacity.

Considering the Cost of electricity in Rwanda, one of the highest tariff in the region of 0.1827$/Kwh (REG,2018), in addition to the low electrification rate of 30% (MINIFRA,2018), it seems impossible to use electricity for cooking and water heating for people leaving in those villages even when electricity is available**.** One of the solutions proposed by Government that could address that energy scarcity was National Domestic Biogas Program (NDBP) Mutabazi.A. (2011). Upon deployment of this program beneficiaries could be households with at least two heads of cattle which is not the case for all households in Rwanda. The cost of that domestic bio-digester is not affordable to everyone especial in rural areas, besides Governmental subsidies, for a 6 m^3 to 8 m^3 volume size bio-digester plant, cost around 1,155 USD and 1365 USD respectively (Dominique, O.2008).

Therefore, this thesis work aimed at designing an economic centralized co-digestion bio-digester plant that will incorporate human waste along with caw dung to supply biogas as alternative energy source to the community in the villages of Gicumbi District, now 5 households have to be connected to the same plant.

This plant, in study, is expected to be economically affordable as the upfront cost as well as Operational and maintenance (O&M) cost have to be contributed mutually among the households that share the same digester system.

1.3. Objectives of study

1.3.1. Main objective

This thesis work intended to design and evaluate the Techno-economic feasibility of centralized co – digestion bio-digester plant that will use human waste (faeces) and manure of domestic animals (caw dung) to generate biogas that has to be used for cooking and heating water in the rural households of Gicumbi District in the Northern Province of Rwanda.

1.3.2. Specific objectives

In order to achieve the objective of this study, the following are specific objectives:

- To design a centralized anaerobic co- digestion bio-digester plant that will provide a reliable energy from biogas.
- To use human faeces in co-digestion to improve the energy security for rural communities.
- To provide affordable and clean cooking fuel for rural households in Rwanda
- To reduce pressure on the forest cutting for firewood gathering and charcoal harvesting in order to enhance the environmental sustainability.

1.4. Research questions

- Is biogas able to provide a reliable energy for cooking in rural households of Rwanda?
- What are the main challenge for diffusion of biogas technology in Rwanda?
- What are the people's perceptions about the use human excreta for biogas generation and use?
- Can biogas be competitive as an alternative fuel for cooking in rural households of Rwanda?

1.5. Significance of the study

This study may serve as reference material for Nation Domestic Biogas Program (NDBP), Energy group (REG), Ministry of infrastructure (MININFRA), and others institutional bodies of knowledge and all Ministries and Development Research Agencies.

In conceptual way, this study empirically sets to provide an alternative cooking fuel to the households, in order to overcome the barrier encountered by National Domestic Biogas Program. The findings of this study will enhance more jobs creation as biogas digesters would be built on a huge number. Therefore, more technicians for operation and maintenance will be needed. This study also will educate countryside people in using clean energy technologies and provides a very rich NPK fertilizers.

The findings of this study further will be of significance to policy makers and stakeholders in the energy sector of Rwanda. It will help on formulating guidelines and improve existing policies that impede diffusion of biogas program.

1.6. Scope of the study

1.6.1. Geographic scope

This thesis work was geographically carried out in Gicumbi District one of the five districts constituting Northern province of Rwanda. Twenty-one villages among 690 were considered, it means one village per sector for Twenty-one sectors of Gicumbi District. Ten households per villages were considered, implying that 210 households were used for the study sample. This study considered Gicumbi District simply because it is one of the Districts of Rwanda with high number of heads cattle and livestock in general, (see Appendix 1) and Northern Province where Gicumbi District includes is one of the Provinces with low forest plantation area, as the major primary energy source in Rwanda, (Appendix 2).

1.6.2. Content scope

This thesis work was limited only at designing and analyzing the feasibility of biogas digester in terms of techno-economy aspects, with the aim of providing biogas that directly has to be used for cooking and water heating. It does not include biogas purification and electricity generation as targeted population that are households in rural areas cannot financially afford the supplies and technological transformations.

1.7. Limitation of study

There are some challenges associated with this study, such as quantification of firewood that are used through poor traditional three cooking stoves in order to know the exact firewood consumption in some households of Rwanda. Also quantification of the exact daily human manure and animal wastes as primary data were constrained by time limit, as time frame for this research was not sufficient enough to record such kind of primary data. Therefore, this study relied on both primary and secondary data from different literatures.

It was not easy to get quality data since the study relied on use of questionnaire, respondent might not have been honest with the answers or be biased and give information out of context of the situation.

1.8 Thesis structure

The main issues to be discussed in this work have been outlined in the figure 2. The thesis work began with introductory remarks, which covers briefly the general global energy situation; background of the study that emphasized on key information about energy in Rwanda; problem statement; objective of the study; research questions, significance of the study; scope that includes both geographic; and content scope; and hence limitations of the study.

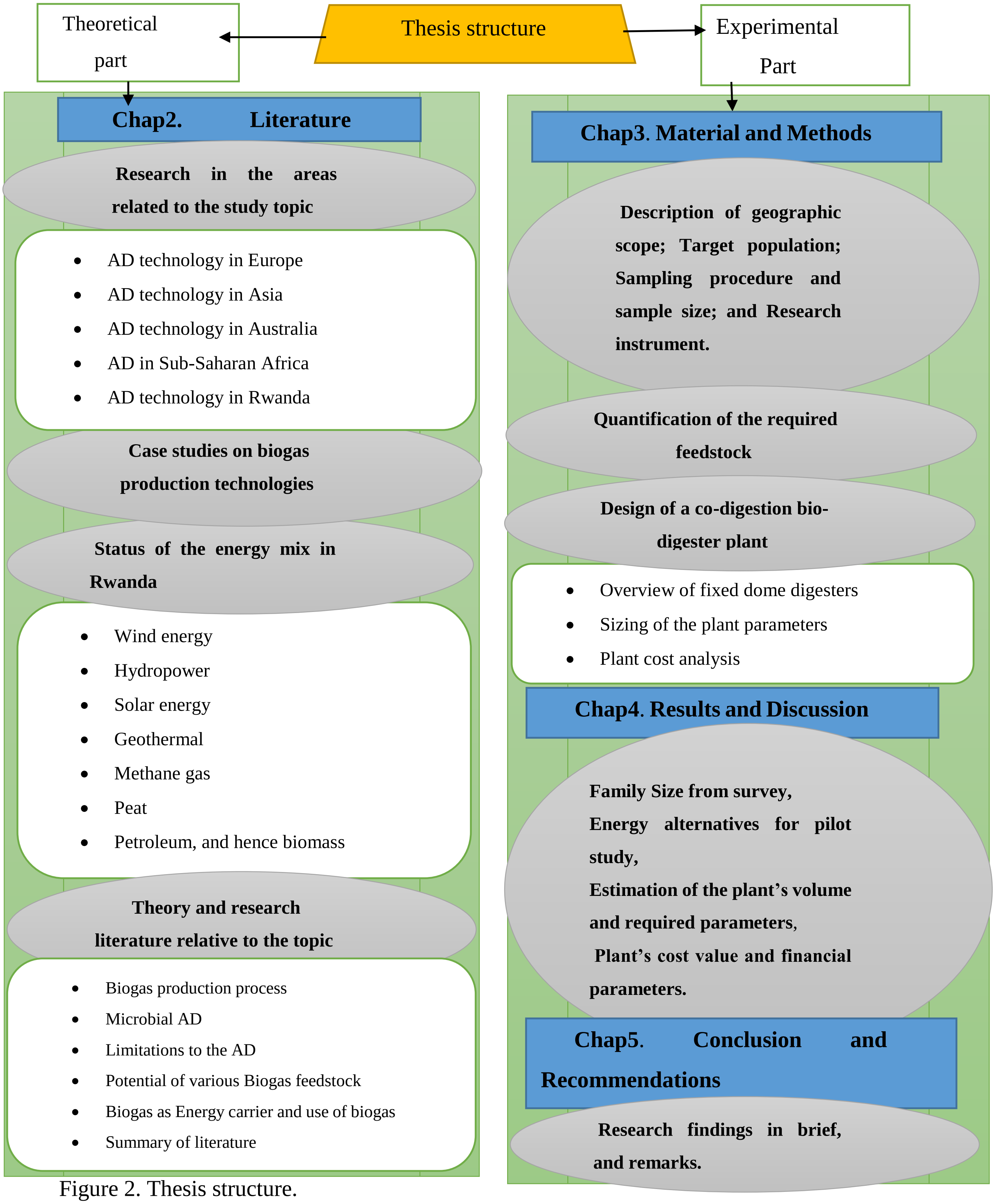


Figure 2. Thesis structure.

CHAPTER TWO: LITERATURE REVIEW

2.0. Introduction

This section reviews the previous works done by other scholars about AD technology around the world for further identification of knowledge gaps necessitated in current study. Also it provides some tangible case studies for biogas technologies applications mainly in sub-Saharan Africa including Rwanda. Further it gives on overview on the current status of energy mix in Rwanda, and emphasizes on the theoretical aspects of AD process and biogas applications.

2.1. Researches in the areas related to the study topic

Globally, according to IRENA (2017), roughly 50 million biogas systems are being used for cooking globally, most of them are in Asia especially China and India. Estimating the use of residential-scale biogas for cooking in developing countries seems challenging, because biogas digester units often are locally sourced and resulting energy provision is rarely measured, but biogas technology has different levels of development and applications from country to country.

2.1.1. AD technology in Europe

According to Nikita, et al. (2015), Europe has been a world leader in adoption of Anaerobic Digestion of municipal solid waste (MSW) since the introduction of the technology in the 1990s. Almost 200 bio-methanation plants for Municipal Solid Waste (MSW) were in operation up to 2010, spread over 17 countries with a total waste treatment capacity of 6 million TPY. Germany is the world leader in this sphere with more than 1.7 million TPY of installed capacity followed by Spain 1.5 million TPY and France 80,000 TPY. Spain, Belgium, Holland, Switzerland, and Germany are among the larger European countries having the highest per capita anaerobic digestion capacities (Poeschl, M. et al, 2010). About 10% of organic waste in Spain is treated in Anaerobic Digesters. In 2009, biogas production of 25 EU countries was equivalent to 16.692 billion m^3 biogas, of them 35.96% from landfill,12% from municipal and industrial sludge anaerobic digestion and 52% from scattered farm, municipal solid waste and centralized co-fermentation biogas projects. From 2006 to 2009, EU biogas production has increased by 70.37% mainly benefited from the increased agricultural biogas projects and municipal solid waste biogas projects. The drivers underlying this growth include: Firstly, a series of landmark directives such as Landfill Directive 199 that set targets for progressively reducing waste from landfills. Renewable Energy Directive 2001 also sets targets for EU members states for the amount of electricity to be generated from renewable.

Secondly this technique became popular in comparison to others such as incineration, pyrolysis, and gasification with poor public acceptance and high development costs. Also, source separation and segregation of the organic fraction of solid waste is a practice actively practiced and encouraged in these countries.

UK

Biogas recovery in UK is mainly from landfill wastes there. The UK Certification System (Renewable Obligation Certification System) requires increased renewable energy power generation from all power supplies greatly pushed forward investment in biogas power. Biomass power generation was 6,143 GW/h as of 2009 accounting for 24.7% of renewable generation (Nikita, J.E. et al.,2015). Government also provides support for R&D, demonstration projects for grid power generation from biogas. Strict landfill taxes and standards have also been imposed and increased the cost of waste disposal.

Germany

According to Poeschl, M. et al., (2010), Germany has the largest installed capacity, over 4000 biogas plants with 1.5 GW, of biogas based electricity. Average electrical capacity of each plant is 400-800kw. Most of the plants are of large scale capacity for treatment of farm waste, MSW, or organic industrial waste. Biogas thus, is an important source of generating electricity or for space heating. The driving forces are mainly preferential policies and incentives. Promulgation of "Grid Integration of Power" in 1990; the "Renewable Energy Act" 2000; and support programmers for biogas power generation created a conductive environment for all types of biogas projects from small farm based digesters to large scale, while also increasing income potential from grid based power generation.

2.1.2. AD technology in Asia

In Asia, tens of millions of small digesters are used in households or on small farms to produce gas for cooking. China, Nepal, India and parts of southeast Asia have seen exceptional uptake of biogas in the past decade. As in other regions, the health, environmental and economic benefits of upgrading to biogas for cooking are substantial.

China

According to Development Status of International Biogas Industry report of 2011, Biometahnation in China has been receiving support ever since 'Great Leap Forward' movement in the 1950's. Energy crisis of 70's also gave a renewed push with a phenomenal increase from less than a million to 7 million plants in a decade. China today has the huge number of individual biogas plant and world's largest biogas program. Main feedstock is animal waste followed by crop residues and vegetable wastes; while gas from the smaller sized plants are used for lighting and cooking. The largest ones are used for electricity, powering agricultural machinery and pumping irrigation water. In urban areas it is run by distilleries, waste disposal and night soil treatment units. As of 2015, more than 25 million Chines households have biogas plants installed. The substantial subsidy offered by the government explains the widespread use of this technology. Their renewable energy support program has five basic components market that includes; development and protection, technical support, price support and cost sharing, and financial support and source utilization. This program encompasses support to biogas energy also. Various measures have been taken to promote manufacturing of biogas plants on an industrial level. Several private companies are coming up with innovative designs to bring down costs, simplify construction and minimize technical defects (Nikita.E.J.,2015).

India

In India family sized digesters began with the implementation of the National Project on Biogas Development in 1981 that was named after National Biogas and Manure Management Program. According to Khoiyangbam, et al (2011) and Nikita, E.J. (2015), the first anaerobic digestion plant in Asia for generating methane from organic waste was installed at Matinga Leper Asylum in Mumbai in 1897. Like most developing countries, India's biogas support program was focused on family sized digesters, considering the rural families with cattle where animal manure and human wastes were used as feedstock. The aim was to provide biogas for cooking, to reduce firewood consumption and deforestation, indoor air pollution abolition as well as improving soil fertility. As of 2015 India had about 4 millions of installed AD systems most of them on family size (Nikita, E.J. 2015).

Nepal

This country have shown a keen interest in bio-methanation following the energy crisis of the 70's.

Households are primary consumers of the energy in Nepal and according to the estimates there are 27.7 million tons of cattle waste generated per year that can be used to meet the fuel needs of over

400,000 households (Nikita.E.J.,2015). It is also viewed here as solution to the increasing deforestation problem and as source of fertilizer. Feedstock for the plant is mainly cattle dung and under the guidance of the Department of Agriculture, Agriculture Co-operatives and the private sectors. In Nepal thousands of biogas plant have been installed in all district, and this is the outcome of planned support programs and incentives. Operational scale of these plants are also good, with 85-90% of them operating as of 2015.

2.1.3. AD technology in Australia

In Australia, the landfill reduction policies of the government and Sydney City planners lead to the construction of a 187000 tons per year AD facility in 2003 generating 2.2 MW of electricity. A 38,500 tons per year, wet digestion facility, built in 2003 also began digesting commercial waste and wastewater treatment sludge. As of 2015, Waste-to-Gas plant were also being set up in many parts of Western Australia such as Perth and Pilbara (Nikita.E.J.,2015).

Various organizations and mechanisms such as Low Carbon Australia, Clean Energy Finance Corporation and Australian Government’s Clean Technology Investment Program provide grant for biogas plant initialization. The Carbon Pricing Mechanism of the government aimed at the largest polluters also targeted landfills that have net GHG emissions.

2.1.5. AD technology in sub-Saharan Africa

According to IRENA (2017), most of the households in sub-Saharan Africa rely on traditional cooking stoves (TCSs), with some 900 million people estimated to rely on TCSs by 2020. Smoke from cooking with TCSs results in 600,000 deaths in the region each year, with an estimated loss of 2.8% of gross domestic product. That includes USD 29.6 billion in lost productive time spent on the fuel gathering and the cooking process. Even though biogas systems have high upfront costs of USD 500 to USD 1500 that is the main challenge for affordability in sub-Saharan Africa, the corresponding lifetime costs are the lowest among cooking technologies. To encourage biogas adoption and realization of its benefits, several international development agencies and country programs have installed biogas systems for free or a reduced cost to households. The Africa Biogas Partnership Program, a Public-Private-partnership, between Hivos and SNV Netherlands Development Organization, had installed 46000 household sized digesters by 2016. SNV-NDO announced plans to extend the program to a further 100,000 households by 2017 in East Africa (Kenya, Ethiopia, Uganda, Tanzania) and West Africa specifically Burkina Faso (IRENA,2015 & 2017). Biogas use in Africa has been mostly from agricultural waste and human excrement in urban settings. This because livestock waste and agricultural residues are hard to collect from widespread grazing lands.

There is a huge need for small scale biogas digesters for cooking activities in households of Sub-Saharan Africa, and nations are trying different alternatives to address this issue. In such, an interdisciplinary workshop that held at Addis Ababa University in Ethiopia in 2011 discussed the potential of small-scale biogas digesters to reduce poverty, to improve the environment in Sub-Saharan Africa, and to reduce deaths due to the indoor air pollution. The main ideas were to explore the most effective, safe and affordable approaches for new technologies to benefit poor people. The workshop focused on the questions related to:

- ✓ The best way to build on the emerging technology of small-scale biogas digesters for development of improved energy supplies, sanitation, air quality and recycling of carbon and nutrients in Sub-Saharan Africa;
- ✓ How to manage the risks that are associated with implementation of small-scale biogas digesters in Sub-Saharan Africa; and
- ✓ Longer term funding or research needed to improve the uptake of small-scale biogas digesters in Sub-Saharan Africa

Small scale biogas digesters are actually emerging technology in Sub-Saharan African Countries. This technology has been implemented in many other countries of the world, and translational research is now needed to support longer term, safe and sustainable implementation in Sub-Saharan Africa. Three main types of digesters are available for use in Sub-Saharan Africa: floating drum, fixed dome and flexible balloon digesters. The Table1 bellow lists the households scale digesters around the world for some selected regions.

Table 1. Household scale digester in the selected countries as of 2014.

Region/Country	Number of unit
Asia	
China	43,000,000
India	4,750,000
Nepal	330,000
Viet Nam	182,800
Bangladesh	37,060
Cambodia	23,220
Indonesia	15,890
Pakistan	5,360
Laos	2,890
Bhutan	1,420
Africa	
Kenya	14,110
Tanzania	11,100
Ethiopia	10,680
Burkina Faso	5,460
Rwanda	1,700
Cameroon	300
Benin	110
Latin America	
Bolivia	500
Nicaragua	280

Source: IRENA, (2017) & Nikita.E.J., (2015)

2.1.6. AD Technology in Rwanda

Anaerobic digestion technology for biogas generation has relatively long history in Rwanda, it has been available since the end of 1990s (SNV,2008). Initially, biogas was promoted at large entities like prisons. By 2000, a number of other institutions including schools and hospitals also started building biogas plants. As of 2013, 68 institutional biogas digesters were operating (Sinaruguriye.J.C, & Habimana. J.B,2013) and as of 2017, a total of 86 institutional biogas digester were already installed around the country.

In 2006 government launched the National Domestic Biogas Program (NDBP) in which 10,588 domestic digesters use animal wastes for biogas were installed in different districts of country (MININFRA,2017). This program was aimed at reaching 100,000 rural household digesters by 2018 (Nyamvumba and Gakuba, 2014). As of 2017, 11 out of 14 prisons in Rwanda were using biogas from toilets livestock for cooking. This reduced the costs of cooking by 50 % if compared to the cost of electricity in Rwanda (Ituze.G, et al,.2017). NDBP was motivated by Governmental subsidies and loans from local micro finance at low interest rate.

The feasibility study carried out by SNV (2005), indicated that Rwanda has potential and suitable environment for biogas technology. Climate varies between 15°C to 30°C which is favorable for psychrophilic to mesophilic bacteria to operate in the digester system. Governmental program of one cow per poor family increased chance for more households to own biogas digester as cow dungs are available. Currently in Rwanda, biogas plants that are constructed are in sizes of $4m^3$, $6m^3$, $8m^3$, and $10m^3$, that use animal wastes to provide biogas for domestic cooking and lighting. For majority of households assisted by NDBP, about 65% were satisfied with functionality of biogas digesters and gas produced 25% of them were disappointed by functionality of their biogas systems, while for 10% of households their plants were not operating at all. Some of the reasons highlighted for failures of the systems were inadequate substrate to feed the plant (cow dung and water) (Bedi et al., 2015). On other hand, some households owning biogas digesters could not give any reason behind its failure when it comes to the technical part where fault might have been done by masons during construction.

The designs of biogas digesters in Rwanda see figure 3, as well as in Sub-Saharan Africa, are of three types that are; fixed dome digester, flexi bags and fiber glass. Research conducted by SNV Rwanda UR-CST on different biogas digester plants, found that the biogas digesters that have been working for at least 5years in good working mode were few. The main reason behind those failure is lack of follow up for technical assistance (Gloria. V, Claude, et al.2015).

Figure 3.Types of biogas digesters found in Rwanda (EWSA)

According to Rwanda Energy Group- National Domestic Biogas Program (REG-NDBP,2015), about 78.3% of fixed dome and 47% fiber biogas digester plants were found in Operation countrywide in 2015.

2.2. Case studies on biogas generation technologies

2.2.1. Case study I: NSTINDA prison sanitation systems in Rwanda built in 2005

The widespread use of septic tanks for prison (and other large institutions) sanitation disposal was a growing health risk. This is done to the fact that generally these large septic tanks were poorly maintained. A program to develop biogas digesters for a number of prisons was undertaken in 2005 with ICRC being the main contractor. The technology used was developed by Kigali Institute of Technology (KIST) and contributes a great deal to fuel needed for cooking (in NSTINDA prison of 12,000 prisoners) the wood required for cooking has been reduced by 30% by powering 12 biogas ovens. The pictures on figure 4 bellow show biogas digesters under construction at NSTINDA prison.

Figure 4. Digesters under construction at NSTINDA prison (source: OXFAM,2011)

For design, a number of $100m^3$ hemispherical fixed-dome digester are connected in series to provide the sanitation in NSTINDA prison. Each system provides treatment for effluent of about 1,000 people with an approximate HRT of 30 days (at 20^oc). Large diameter inlet/outlet pipes are used to avoid clogging and large channels are built between the domes to allow slurry movement between them, in which each dome has its own displacement tank.

2.2.2. Case study II: CYANGUGU prison sanitation system built in 2002

Biogas plant at CYANGUGU prison see figure 5, treats the toilets waste from prisoners by using fixed dome anaerobic digesters. Generation of biogas was achieved to generate energy for cooking that saved about 80% of fuel required for cooking activities in this prison. This was come out as a sustainable solution for waste treatment as well as energy provision for 6,000 inmates.

Figure 5. Biogas digester at CYANGUGU prison (Butare and Karamo,2002)

Infact, a bioreactor is fed through two toilet-waste flows, one comes from 4,500 prisoners and the other from 1,500 prisoners. One digester of $150m^3$ is divided in two shells to improve performance, with a storage capacity of 28 m^3 and two holding tanks to further stabilize slugde. A production of 75,000 CH_4 L/day with a 30 m^3 gas line which feeds 4 stoves of 1200 L (Butare,A. & Karamo, A., 2002). The fluent from biogas plant is reused as fertilizer in crops inside the prison (2ha) of bananas,coffe, soy and tomato.

2.3. Status of the energy mix in Rwanda

Rwanda is endowed with different energy resources including wind, solar, hydro, methane, peats, Biomass and Geothermal in which a huge amount of these resources are still untapped. As such, biomass is still the major source of energy with 85% of share in primary energy mix (Uwisengimana J.D., et al,2017)**,** and imported petroleum products account about 40% of foreign exchange. See figure 6 representing Rwanda's energy consumption balance.

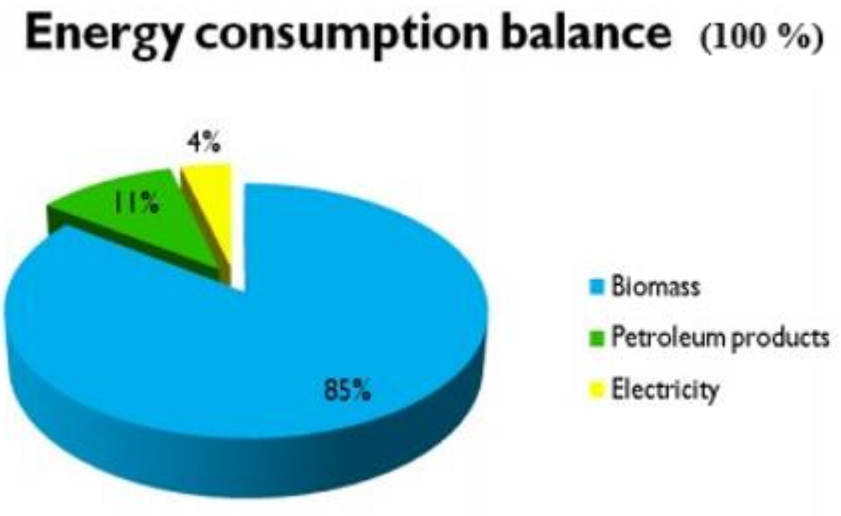


Figure 6. Diagram of Energy mix in Rwanda
(Uwisengimana. J.D., et al,2017 &, Mininfra,2011)

2.3.1. Wind energy

Currently in Rwanda, there are only two sites where wind energy has been used, the first site is in Gabiro where wind turbine is installed for water pumping with power of (3 m^3/h). The second one installed by private person to supply 1kw electricity to a cyber-network in Remera – Kigali, and the third one at National Radio and Television headquarter used to power FM transceiver antenna. However, it was destroyed in 1994 during genocide (Ituze. G. et al.,2017)**.** Rwanda has an average wind speed which varies from 2 to 5.5 m/s and direction of wind which varies from 11° to 16° Est-West (Kirezi.S et al., 2004). According to national meteorological agency, Rwanda has identifiable regions for wind exploration. These are Kanombe airport in Kigali, Kamembe airport in Rusizi District, Gisenyi, Nyagatare and Butare in South province among others.

2.3.2 Hydropower

Rwanda’s major rivers have proven 333 potential sites for micro-hydropower. Potentials opportunities exist in Micro and small Hydropower Projects and shared regional hydropower projects with EAC partners. The largest domestic hydro-power project is Nyabarongo I with an installed capacity of 28 MW (MININFRA,2018). Some shared hydropower project with neighboring countries are also underway, including 145MW project shared by Burundi, Republic Democratic of Congo and Rwanda and 80MW project to be jointly developed by Tanzania, Burundi and Rwanda.

To date, 21 hydropower plants are grid connected. They include national and shared regional project (Rusizi I and Rusizi II) between Rwanda and RDC. Hydropower makes up approximately 60% of the total installed capacity (Uwisengimana. J.D, et al,2017). Hydro power plants are either publicly owned and operated, or leased to private companies or privately owned (MININFRA,2018). Table 2 at next lists the on-grid hydropower plants with the relative capacities.

Table 2. Hydropower plants and total on-grid installed capacity

No	**Power plant station name**	**Capacity (Mw)**
1	Ntaruka	11.5
2	Mukungwa I	12
3	Nyabarongo I	28
4	Gisenyi	1
5	Gihira	1.8
6	Murunda	0.1
7	Rukarara I	9
8	Rugezi	2.4
9	Keya	2.4
10	Nkora	0.6
11	Cyimbili	0.3
12	Mazimeru	0.5
13	Nshili I	0.4
14	Musarara	0.4
15	Mukungwa II	2.5
16	Rukarara II	2.4
17	Giciye	4
18	Rusizi I	30
19	Rusizi II	44
20	Nyiramuhombohombo	0.5
21	Agatobwe	0.2
Total		**153.57**

Source: (Uwisengimana. J.D, et al,2017), (REG,2017), (Ituze, G. et al, 2017)

2.3.3. Solar Energy

Rwanda is well benefit with solar energy. Even during the rainy season there is sufficient sunshine, the average daily global solar irradiation on the tilt surface has been estimated to 5.2KWh/m^2/day from Photovoltaic Geography Information System (PVGIS), Habyarimana. F. & Hans G. B., (2017). And the long term monthly average daily global irradiation ranges between 4.8 kWh/ m^2/ day in May location of Burera, to 5.8 kWh/ m2/day in July location of Nyanza, and this indicates a good potential for solar energy development. Due to that potential 8.5 MW plant at Agahozo-Shalom Youth Village, in Rwamagana District, Eastern province of Rwanda was deployed. 20 hectares of land and 28,360 photovoltaic panels have been used for this plant. And it produces 6% of the total country's electricity supply (Rutibabara.J. B et al.,2018). The number of others solar power plants with total installed capacity are shown in Table 3.

Table 3.Current solar power plants in Rwanda

No	Plant name	Installed Capacity (MW)
1	Jali	0.25
2	Ndera	0.16
3	Gigawatt/Rwamagana	8.5
Total		8.91

Source: (Rutibabara.J.B.et al.,2018 & REG, 2017)

2.3.4. Geothermal Energy

Currently geothermal potential, in Rwanda, is estimated to be at about 740 MW in the form of hot spring along Lake Kivu belt (Rutagarama, U.,2015 & Ituze, G., et al.,2016). Previous studies have indicated thermal waters reservoirs with up to 15^{o}C temperature with the most promising geothermal areas located in Karisimbi and Kinigi. The Government of Rwanda considers these geothermal resources as commercially viable for power generation by the mean of either binary or condensing steam turbines**.** According to MINIFRA (2015), development of geothermal resources has been given more priority in the EDPRS II. The known sites are; Kinigi with 200 MW, Karisimbi 320MW, Gisenyi with 200 MW and Bugarama with 20 MW of geothermal potential resources (MININFRA, 2015).

2.3.5. Methane gas

Methane gas is found in Lake Kivu at the estimated potential of 55 billion m^3, with 39 billion m^3 economically exploitable and equivalent to 32toe. Lake Kivu is positioned between Rwanda and DRC with area of 2,400 km^2, and resources from it are equally shared between the two countries. The highest concentrations of naturally occurs methane gas and carbon dioxide are found at depths ranging between 270 - 500 meters (MINIFRA, 2014). Currently KivuWatt Power Station deployed in 2016 is generating and supplying 26 MW of electricity to the national grid (REG,2017).

2.3.6. Peat

According to the African Development Bank report of 2013, several sites with peat energy resources have been identified in country. Those include Rwabusoro, Akanyaru, Murigo, Gihitasi, Mashya, Gishoma, Rucahabi, Cyato, Cyabararika, Nyirabirinde, Kageyo, Kaguhu, Mashoza, Gasaka, Bahima, Bisaka, Rwuya, Nyabugongo and Rugeramigozi. First masterplan on peat in Rwanda, was developed in1993 and to date peat is used in Cement production by CEMERWA and as cooking fuel in small decentralized institutions. The potential of peat in Rwanda is about 155 million tons of dry peat that covers 50,000 hectares of land (Ituze, G. et al.,2016)**.** Available potential for peat resources is estimated at 700 MW, with operating 15 MW peat power plant in Gishoma and ongoing Hakan Peat Power Plant that will generate 70 MW (MININFRA, 2015).

2.3.7. Petroleum

Rwanda relies on the import for its petroleum products. Consumption of petroleum products is getting higher with increases in the economy of country. Import of petroleum products increased from 2.5% to 5.5% in period OF 2000-2012. As of 2015, domestic storage reserves to cover during petroleum shortage was 30 million liters with target to reach 150 million liters by 2017(MININFRA, 2015).

2.3.8. Biomass

In Rwanda, biomass is used in the form of firewood, charcoal or agricultural residues particularly for cooking and heating water in households. It is also used in small industries such as tea factories (MININFRA, 2008). Biomass meets 94% of the national energy needs in rural areas and 85% in the country in general. The balance is met by other alternatives like kerosene, diesel, dry cells, grid and non-grid electricity, biogas, solar, wind and other renewable energies. Previous studies have mentioned that wood-fuel consumption per capita was of 314 kg/year for fuelwood and 134 kg/year for charcoal, with total residential wood-fuel consumption of 2.7 million tons per year. Kigali city alone accounts for 120,000 tons for charcoal consumption which is equivalent to 1.2 million m³ or 850,000t of wood per year (Word Bank, 2011). Figure 7 shows domestic firewood gathering and wood stock at Murindi tea factory.

Figure 7. Domestic firewood and Murindi tea factory firewood (National land center report,2009).

Table 4 bellow shows the wood-fuel consumption in Rwanda as of 2011.

Table 4. Annual wood-fuel consumption in Rwanda (tones per year)

Year	2005	2006	2007	2008	2009	2010
Fuelwood in urban areas	81,916	86,831	92,041	97,564	103,417	109,622
Fuel wood rural areas	2,805,431	2,871,907	2,939,317	3,007,623	3,076,787	3,146,746
Wood for charcoal in urban areas	1,643,655	1,732,734	1,836,698	1,946,900	2,063,714	2,187,537
Wood for charcoal in rural areas	123,409	126,333	129,298	132,303	135,346	138,424
Wood for industries/institutions	336,652	344,629	352,718	360,915	369,214	377,611
Total	**4,982,063**	**5,162,434**	**5,350,072**	**5,545,305**	**5,748,478**	**5,959,956**

Source: (REMA, 2011**)**

Lack of reliable alternative energy sources in households are increasing pressure on the forest resources for firewood and charcoals. According to World Bank report of 2006, charcoal is preferable fuel in the urban households. The trend toward urbanization has increased its demand which pushed up its price, therefore, charcoal market turnover with US $30 million by 2006. Figure 8 bellow indicates the traditional kiln for charcoal processing along with the forest scarcity.

Figure 8. Traditional kiln for charcoal processing with excavated forest due to charcoal harnessing (Source: REMA, 2009)

2.4. Theory and research literature specific to the study topic

2.4.1. Biogas production process

Biogas is a methane rich gas, which results from anaerobic digestion that breakdown the organic material in the absence or presence of oxygen. Anaerobic digestion convert the energy stored in organic materials present in organic matter into biogas. When converted, biogas can either be used directly for cooking through biogas stoves. Biogas can be used to generate electricity from thermo- electric power plants through generating steams that run the steam turbines. Biogas can also undergo further purification and upgrade processes to generate diesel that is used in the vehicles. Biogas digestate constitute a very good fertilizers (NPK) that is useful for crops (Abbas.T, et al., 2012). The use of Anaerobic Digestion (AD) technology has been expanded in recent times following the widespread concerns of researchers for the use of sustainable renewable energies. Due to several effects of greenhouse gas (GHG) on climate change as a result of fossil fuel consumption has led to the growing interest in biogas production to curb the situation (Akoore. A.,2018). The figure 9 shows the stages undergone during biogas production and biogas products use.

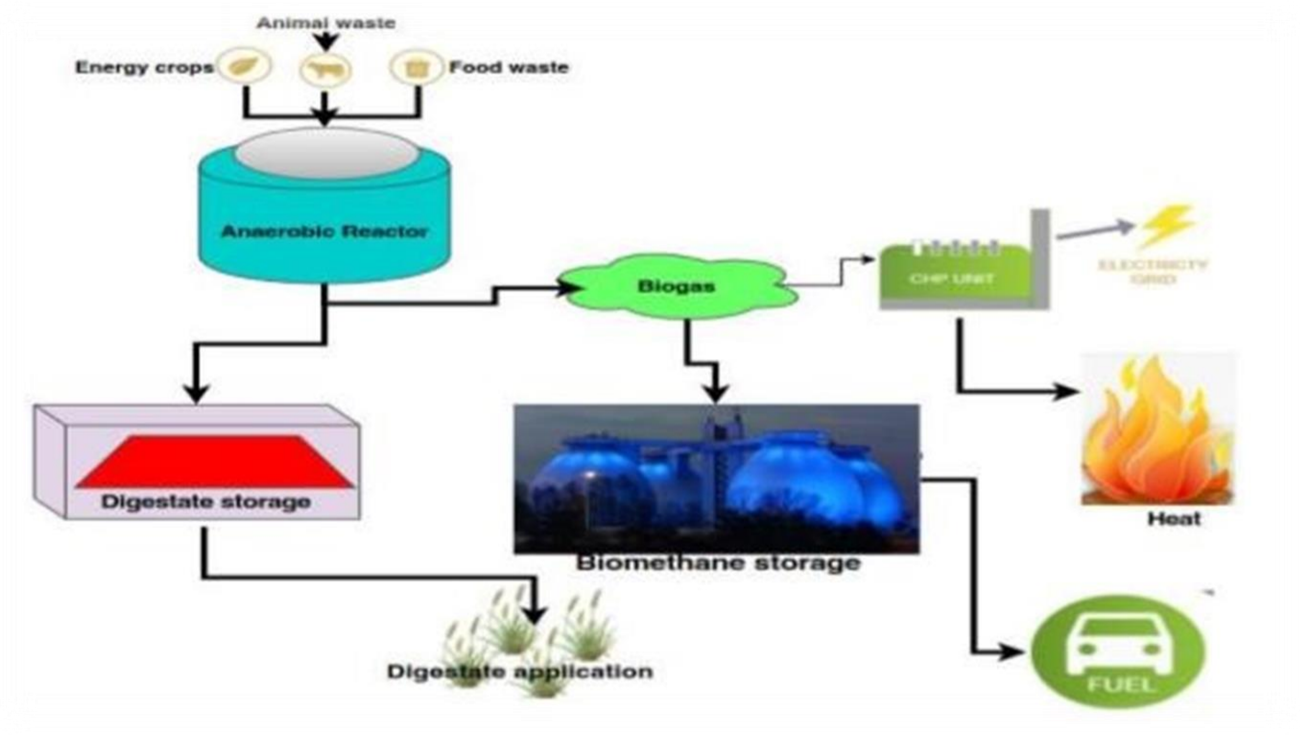


Figure 9. Biogas transformation process and use (Akoore, A.,2018)

2.4.2. Microbial Anaerobic Digestion

Anaerobic digestion is a microbial process where the biodegradable material is converted into methane in the absence of oxygen. The process takes place in a gas-tight cylinder called a digester with the support of biological actions (Christy, E., et al.,2013). The gas produced in the anaerobic digestion predominantly comprise of carbon dioxide (CO_2) and Methane (CH_4), with a certain fractions of other element gas such as; ammonia (NH_3), hydrogen sulfide (H_2S), and hydrogen (H_2) (Gerardi,2003). Anaerobic digestion is a complex process that involves a variety of biological activities. Microorganism and part of the controlling factors influence the optimal performance for biogas realization. The process steps in anaerobic digestion are sequentially connected to each other. Every phase step has different symbiotic bacteria reaction. Therefore, one end process marks a beginning phase for another process. In general, anaerobic digestion process comprises of four biochemical groups; hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Christy, E., et al,2013). Each stage has different function to perform. In most of the cases hydrolysis lead to fermentation whereas acetogenesis and methanogenesis are closely related. Hydrolysis process consists of bacteria that breakdown irregular substrate into smaller units. These small pieces are integrated to fermentation stage and further microbial catalization. Fermented products containing CO_2, H_2S, and acetate are moved to the final stage for methanogenic processing. Purified methane content is collected as the useful final product while other fractions of gases are treated before expulsion (Gerardi,2003). The steps involved during microbial anaerobic digestion process are depicted in figure 10.

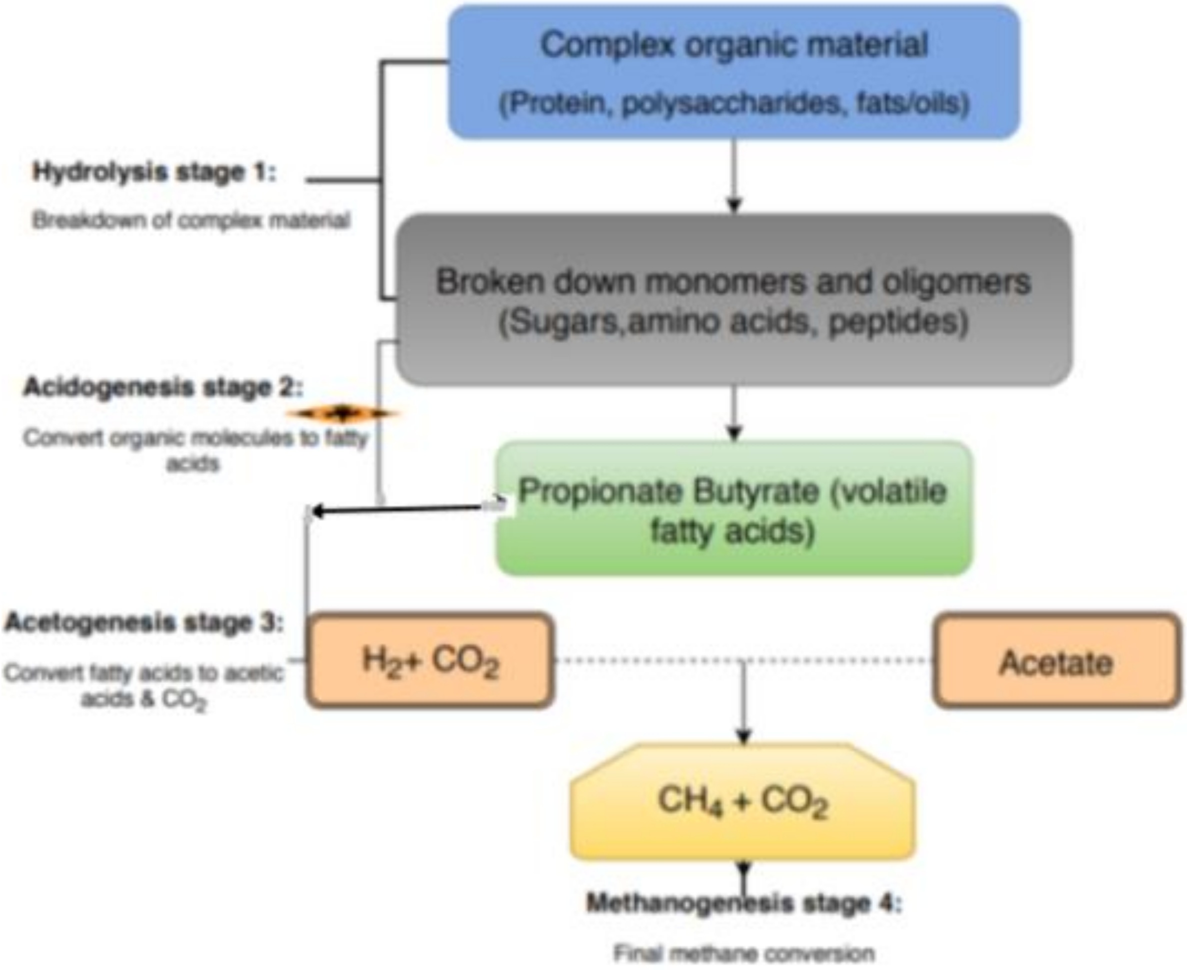


Figure 10. A flow diagram of Microbial AD process (modified from Burgess, C. & Akoore, A.,2018)

Hydrolysis

During this process, complex polymers like carbohydrates, proteins and fats are degraded into sugars, amino acids and long chain fatty acids respectively. This breakdown process occurs primarily through the activity of extra cellular enzymes (lipases, proteases, cellulases &and amylases). These enzymes are secreted by hydrolytic bacteria attached to the polymeric substrate (Franke-Whittle, I.H,2009). This stage plays an important role in ensuring that enough chemical reaction is taken place to prepare the soluble content to the next chemical stage. The hydrolysis steps consist of unique procedures such as enzyme reaction, adsorption, and diffusion (Cirne et al,2007). Substantially, all chemical enhancements assist in smooth and higher methane production.

However, the challenge associated with hydrolysis is commonly found in organic waste but most can be composed by reagent chemical application (Vavilin et al, 1997).

Acidogenesis

The acidogenesis step is operationalized by a microbial process known as acid forming fermentation. It is the second step in bacteria consortia of anaerobic process. The microorganism in acidogenesis stage further transform the hydrolyzed content into small organic acids. The nutrients ratio of carbon dioxide and hydrogen is categorized into 70% volatile fatty acids (VFA) and 30% of alcohols (Al Sead et al.,2012). The organic acids are subsequently converted to acetic acid and hydrogen through acetogenic bacteria. The reflective conversion factors in acidogenic phase are mostly glycose to ethanol and glycose to propionate (Ostrem & Themelis,2004).

Acetogenesis

In this stage, the fermentation products such as alcohols and organic acid are digested by acetogenic bacteria to produce acetic acids alongside with hydrogen and carbon dioxide. The critical element in acetogenesis is hydrogen, and this is because without the presence of H_2 concentration no chemical reaction could take place (Ray et al.,2013). The temperature in acetogenesis is quite an important parameter since it affects the thermodynamics of acetogenic reactions (De Bok et al 2004). The interspecies electron transfers in methanogenic propionate degrading groups is influenced by the chemical reactions at the previous steps. Formation of hydrogen from organic acids becomes stronger at higher temperatures whereas, in methanogens phase, H_2 consumption becomes less energetic (Akoore, A.,2018)

Methanogenesis

Methanogenesis is the final step and the most crucial stage in the anaerobic digestion process. This stage is regarded as the slowest biochemical reaction process when compared to others. This depends on process conditions such as feedstock composition, pH, temperature, and retention time cannot be underemphasized. Methanogenesis is a sensitive and critical step in anaerobic digestion during methane production with less substrate content (Al Seadi et al.,2008).

During this process, the already formed acetate, hydrogen, and carbon dioxide from the previous stages are further transformed into CO2 and CH4 through methanogenic process. It is estimated that two-third of the total produced methane from acetic acid (alcohol) comes from acidogenesis stage.

The remaining one-third comes from carbon dioxide reduction by hydrogen (Ostrem &Themelis,2004). Various constituents generated from biogas digestion process are shown in Table 5.

Table 5.Products of Anaerobic Digestion process

Component	Symbol	Percentage (%)
Methane	CH_4	52-78
Carbon dioxide	CO_2	25-45
Hydrogen	H_2	0-1
Ammonia	NH_3	<1
Water vapor	H_2O	2-7
Oxygen	O_2	<2
Hydrogen sulphide	H_2S	<1

Adapted from (Burgess.C.,2018 & Pullen, 2015**)**

2.4.3. Limitations of AD process

In general, factors that affect performance of an AD includes environmental sensitivity such as; pH values, temperature and moisture), organic loading rate (OLR), hydraulic retention time (HRT), characteristics or biodegradability of substrate, mixing substrates, free ammonia concentration, design of bio digester and skilled manpower (Cioabla, A.E., 2012 & Nikita. E.J.,2015). However, due to the sensitivity of these conditions above, the accurate study and planning need to be taken seriously in order to ensure the stability and efficient performance in methane generation process.

Environmental sensitivity

Temperature

The operation temperature in biogas production is an important factor since it influences the microorganism in the reactor. Therefore, unstable temperatures in the digester will authorize low biogas yield. The relationship between temperature and microbial organisms are intimately connected during AD process. Temperature creates enabling environment to support the growth and functionality of the microorganism (Khalid et al.,2011). There are three main temperatures in AD process, such as psychrophilic, mesophilic, and thermophilic. And the predominant used temperatures are mesophilic and thermophilic, due to their flexibility to adapt on sudden changes (Kim et al, 2002).

Each of these temperatures has their advantages and disadvantages about microbial performance. In thermophilic conditions, high methane yield can be produced at high loading rate, it is also possible to achieve shorter retention time at high temperature, and this increases the reactions of the degradable materials in the reactor. The drawback with the thermophilic is the fact that, it becomes more difficult to control when there is a sudden change in temperatures, and it is also energy intensive, according to Akoore, A.A., (2018).

On the other hand, mesophilic conditions are widely recognized in biogas production due to its reliability and energy efficiency, hence commonly used than thermophilic. The best operational temperatures are considered within 35 ^{o}C to 37^{o}C and any changes made slightly below or above that figure will render reduction in biogas production (Khalid et al.,2011). Merit of mesophilic digestion is the fact that, longer retention time is needed for this process which often leads to low biogas yield, but it is the most commercially suitable type. Different types of AD process with associated temperature ranges are mentioned in Table 6.

Table 6. Typical operational temperature of AD system

Anaerobic process	**Process temperature (^{o}C)**	**Hydraulic retention (days)**
Thermophilic	**50-60**	**15-25**
Mesophilic	**30-37**	**25-30**
Psychrophilic	**10-25**	**>50**

Adopted from (Cheng,2017) & (Akoore.A. A,2018)

pH values

This process condition is very crucial in anaerobic digestion and can affect the yield of the biogas plant. The operational principal of pH in AD process affect the products and a digestive system largely. The microbial organism in the digestion system which facilitate the degrading of the feed stock require different optimal pH condition for productive growth. Therefore, it is vital to take into account the necessary steps to ensure a sufficient balance of pH for suitable microorganism process (Akoore, A.,2018).

Studies have mentioned that the optimum pH condition for methanogenesis is between 6.5 to 7.2 (Skeete,2016). **S**ensitive nature of the microorganism in methane production during acid condition requires optimal pH values. Nevertheless, pH value could be maintained at 5-7 in hydrolytic microorganism process (Veeken et al,2000).

Moisture

The amount of water in anaerobic digestion is imperative thus facilitate the process condition of the AD, whereby the moisture ratio in the system influence the final yield properties according to Christy, E., et al., (2013). However too much or little water could affect the process performance hence leading to relative quicker or slower dissolution of the organic material. Research has shown that maintaining the stability of the moisture is tricky and sometimes uncontrollable, it further suggested that methane yield can be best obtained at the range of 60-80% humidity (Bouallagui et al.,2003).

Hydraulic retention time (HRT)

Retention time often refers to the required time for substrates to stay in digester. It can also be expressed in an equation form such as RT=V/Q, where RT means retention time (number of days), V= Volume of bio degraded feedstock in m^3, and Q= Volumetric flow rate of feedstock in m^3/day (Akoore, A.,2018). Retention time for biogas production depends on different factors such as; process temperature, feedstock composition, and digester volume among others. Retention time affects the growth of the bacteria in the reactor. According to Gonzalez- Fernandez et al (2015), maximum methane yield can only be possible if retention time is reduced while an increases in loading rate of the reactor (Christy, E., et al,2013).

Mixing of substrate

Mixing is an important physical process for better anaerobic digestion. This process is aimed at setting a uniformity of all individual input materials. More attention is shifted to temperature, material concentration, and some environmental factors. According to Weiland (2010), mixing is important so as to prevent substantial deposition of organic matter in the reactors.

Carbon to nitrogen (C/N) ratio

Carbon to nitrogen ratio plays a crucial role in methane production during AD process. This ratio contributes to effective microbial growth in reactor. Failure in the proportional ratio of these nutrients yield low methane production**.** Optimal ratio for C/N are 20 and 30, respectively, anything different from these considerable ranges can results in bad products such as ammonia accumulation or high consumption of nitrogen (Weiland, 2006). However, according to Khalid et al., (2011), balancing of C/N ratio can be done through a substantial low mixing of different substrate nutrients.

Skilled manpower

As the whole process of engineering anaerobic digestion has to be highly regulated, only skilled persons with a proper understanding of all the steps in the process can effectively handle the plant. This expertise may be found to be lacking in developing countries and training or employing qualified people may form a large part of the initial capital costs.

Upfront cost

Most often the high initial costs of setting up an anaerobic digester, especially of medium and large scale level are the biggest inhibiting factor to its set up. Even from a large industrial project to a family size plant the capital expenditure can be unfordable**.**

2.4.4. Potential of various Biogas feedstock

To analyze the energy and biogas potentials of the available feedstock while planning a biogas plant is a very essential point. This approach will inform whether or not available feedstock worth the energy requirement for the facility into consideration. Thus, evaluation of methane production potential must be a pre-initial decision phase for a given biogas business. Table 7 bellow shows the biomass properties for selected feedstock.

Table 7. Biomass properties for Anaerobic digestion process

Source	Waste amount (Kg /day)	Dry Matter (% total mass)	Dry organic matter (% of DM)	C: N Ratio	Moisture (%)	Biogas yield m^3/kg of dry organic matter
Caw dung	20-30	7-20	65-85	16-25:1	80	0.2-0.4
Pig dropping	3.00-4.00	13	74.4	6-14:1	87	0.35-0.59
Human manure	0.40-1	15-35	80-92	5-16:1	65-85	0.24-0.65

Source: (Andriani,D.et al.,2015; Molla, A.,2014; OXFAM,2011; Colon.J., et al.,2015 & Akoore, A.,2018)

2.4.5. Biogas as energy carrier

Table 8 bellow shows the energy content of biogas products from Anaerobic Digestion (AD) process.

Table 8. Energy values of biogas products

Property	CH_4	CO_2	H_2S	H2	Biogas
% by volume	52-78	25-45	1/10	0-1	100
Energy content (Kcal/l)	9.0	-	-	2.9	4.713

Adopted from: (Nikita, E. J.,2015)

Energy equivalence of $1m^3$ of biogas with 60% methane is equal to 4713 kcal (Nikita, E.J.,2015). However, when biogas is converted into electricity through a biogas powered generator about 2 kwh of useable electricity is produced from $1m^3$ of biogas, and other part of energy turns into heat that can also be used for heating process through heat recovery technology. More the methane content in biogas is high, the higher is energy equivalence as calorific value of methane is diluted by the presence carbon dioxide and other trace of gases.

An equivalence comparison of biogas at 60% methane content with other cooking fuels is shown in the Table 9.

Table 9.Biogas fuel equivalence

Biogas	**Other fuels**
1 m^3	0.714 littles of petrol
1 m^3	0.64 littles of diesel oil
1 m^3	0.620 little of kerosene
1 m^3	4.698 kwh of electricity
1 m^3	0.45 kg LPG
1 m^3	0.43 kg of butane
1 m^3	2 kg of charcoal
1 m^3	3.5kg of firewood
1 m^3	12.30kg of Cattle dung

Source: (Khoiyangbam et al,2011; Molla, A.2014; Nikita, E.J.,2015, OXFAM,2011 & Sachn, K.,2018)

2.4.5. Use of the Biogas products

Biogas can be used for a variety of energy services, such as heat, electricity and vehicle fuel (Seadi, et al.,2008; Shuncheng.Y.,2010). It can also be burned directly for cooking and lighting. The direct burning of biogas in boilers is the simplest way to utilize biogas, which does not need any upgrading. Biogas can produce heat either on site, or distributed through pipeline to the end user. It is also used to generate a combined heat and power (CHP) which is a very efficient way of using biogas to generate energy with about 90% of efficiency. After upgrading process, biogas can be used as vehicle fuel or injected into the natural network used as natural gas. Upgrading process removes all contaminants such as carbon dioxide and hydrogen sulphide throuhg which methane content get increased from 50-75% to more than 95% (Seadi,et al.,2008). In addition,methane and carbon dioxide from biogas can be used to produce chemical products as an alternative to fossil sources. Flow chart on the figure 11 describes further applications of biogas products.

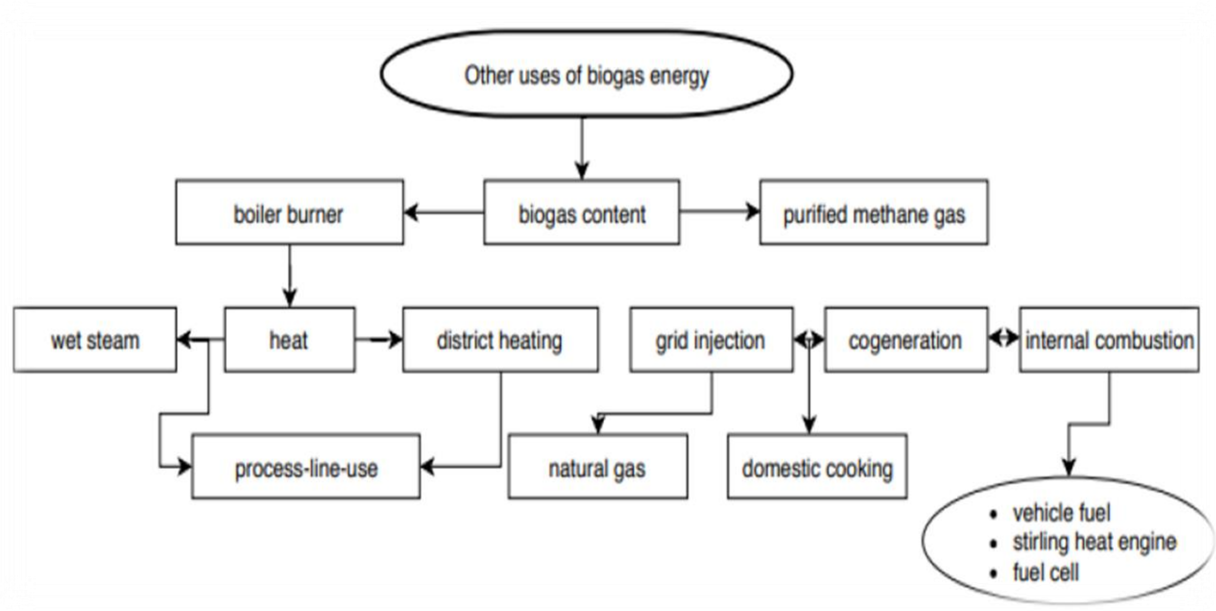


Figure 11. End use of biogas product: (Adopted from Akoore.A.2018 & Weiland, 2010)

2.5. Summary of the literature review

In summary, based on the literature reviewed, biogas technology is an emerging / non-mature technology. It has a long history in some countries especially from Asia and Europe. It can be a competitive alternative fuel for mitigating the climate change raised by the use of fossil fuels, as well as hygiene provision. Biogas was found to have so many applications ranging from domestic to industrials uses. Biogas has proven to have various derivations that includes; household wastes, agricultural wastes, industrials wastes, Municipal Wastes, Landfills wastes and so many others. Several researches have been done for optimization of biogas technology, among the other renewables sources, in order to meet the global energy demand that is increasing with the global population growth.

However, more attention in previous researches was put on the large scale entities for electricity generation or for cooking. Household considerations were few, and among them they only emphasized on the use of animal wastes for biogas production especially in Rwanda. But, the researches failed to mention other alternatives for biogas deployment and use at domestic level when the animal wastes are not sufficient enough or not economically affordable as the only feedstock to supply the energy required through biogas.

Frequently, the biggest challenge for dissemination of biogas technology mainly in Sub- Saharan Africa, is the highest upfront cost as mentioned in the literature. In the most of the cases high initial capital is afforded due to donors from various organizations as incentives or subsidies from the Governments. The researches also failed to mention what if the subsidies from the Government are not enough relative to the financial capacity of a beneficiary to deploy a biogas system at his/her home.

Therefore, to complete that knowledge gap, this thesis work focused on the domestic level digestion technology. This will incorporate human faeces with manure of domestic animals as a co-digester biogas plant in the case of low access to the raw material for biogas provision at home. To address the financial constraint, this thesis work suggested a centralized system with a small limited number of houses, so that the upfront cost should easily be contributed among them for the system to be economically affordable.

This study hence needs to contribute to knowledge by providing this co-digestion technology as one of the measures to improve biogas dissemination in the country, in which the feedstock availability for domestic level was among the major challenges for biogas deployment and development in Rwanda.

CHAPTER THREE: RESEARCH METHODOLOGY

3.0. Introduction

This chapter firstly describes the geographic scope of study, various stages and phases followed in data collection, co-digestion biogas plant designing procedures, as well as the economic analysis. Specifically, the following subsections were included; research design, target population, sampling precedures, data collection instruments and data collection procedures.

3.1. Description of the pilot scope

Gicumbi District is one of the five Districts constituting North Province of Rwanda. Gicumbi has total population of 397,871 in habitants, density of 480person /sq.km and 829 km^2 of the surface area. Gicumbi District is characterized by low hills and valleys, with average altitude of 2100m above the sea level, an average temperature between 15^{o}C to 30^{o}C, and annual precipitation of approximately 1.400 mm. Gicumbi has two main season: a heavy rainy season that occurs from March to May and a long dry season between June and October. The regional economy is essentially agriculture with approximately 90% of the population participating in the agriculture sector. Currently, over 76000 heads of cattle in which 22,500 of them from governmental Girinka Program, (which is literally one cow per poor family program), are available in District. It is composed of 21sectors, 109 cells and 690 villages. As of 2017, a total of 429 domestic biogas plants were constructed in Gicumbi District. Figure 12 shows administrative map of Gicumbi District.

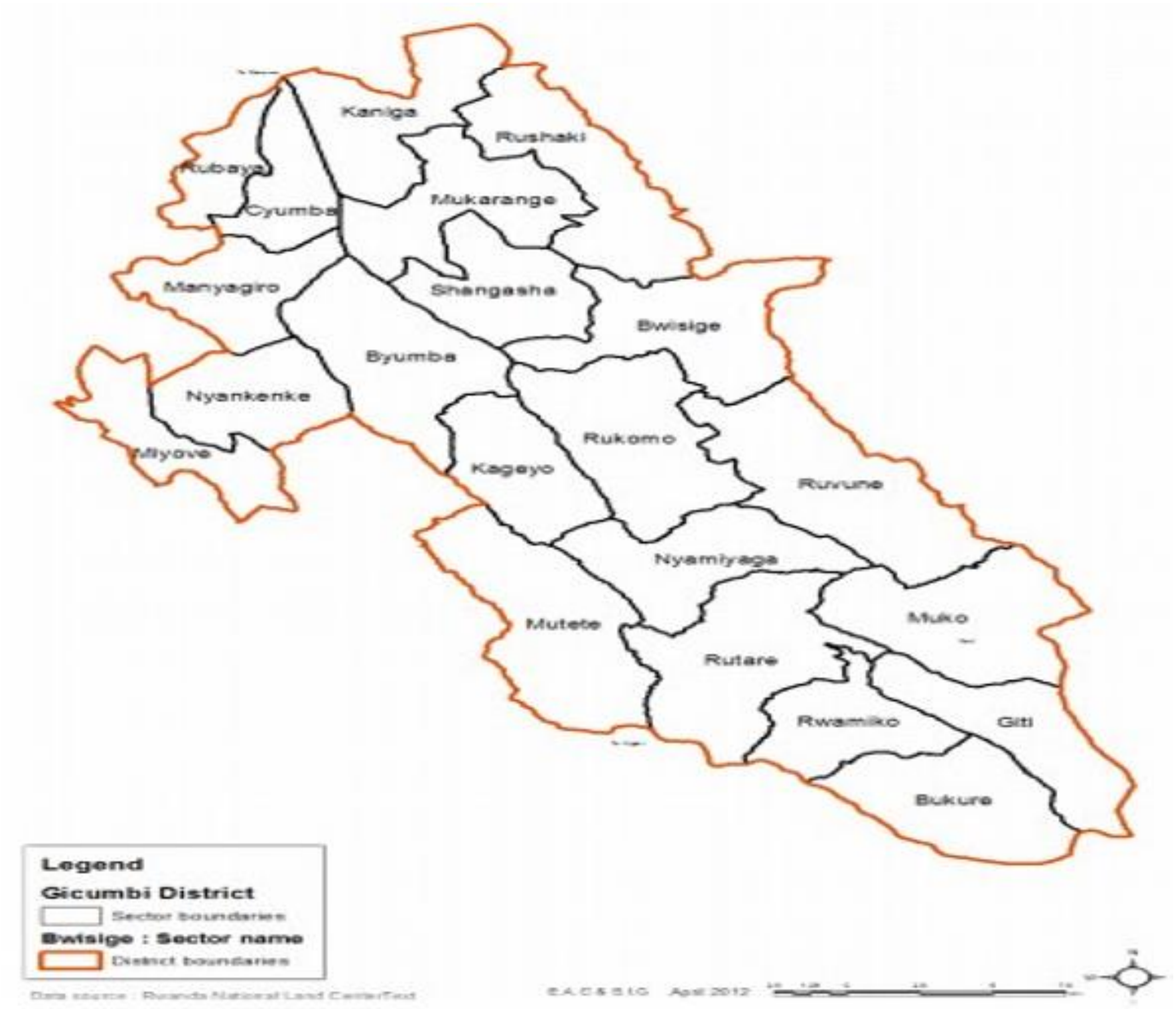


Figure 12. Administrative map of Gicumbi District (Rwanda Natural Resource Authority, 2015)

3.2. Research Design

According to Kothari (2004), research design is a plan for obtaining answers to the questions being studied and for handling some of the difficulties encountered during the research process. It is therefore, the arrangement of conditions for collection and analysis of data in a manner that aims to combine relevance to the research purpose with economy in procedure. Descriptive survey was used for this study.

3.4 Target Population

This study was carried out on 21 villages of 21 sectors of Gicumbi District, considering one village per sector. Total study population was 210 households taking 10 households per village. The study included households having operational biogas digesters. This was to understand whether there are some challenges and/or benefits of NDBP. It has also included, the households with non- operating biogas digester. This was aimed at understanding their reasons to do not have that facility and to measure the energy expenditure while using energy alternatives other than biogas for cooking and water heating. The results from the survey is shown by Table 10 bellow.

Table 10. Biogas status for the respondents

Category	Number of households
Operational domestic biogas plants	1
Non-operational domestic biogas plants	5
Without any biogas plant so far	204
Total	210 Households

3.5 Sampling Procedure

Simple random and purposive sampling techniques were used to ensure that each member of the target population has an equal and independent chance of being included in the sample. The random sampling methodology was chosen to minimize sampling bias because the category of households has a large population size. Purposive sampling technique was used because sampling has to be done from smaller groups of informants. Therefore, researcher needs to choose one by one purposively. The responses from the interviews with different selected participants, both quantitative and qualitative data were collected.

3.6. Data Collection Procedure

Burns and Grove (2010) define data collection as the precise systematic gathering of information relevant to the research problems. This may use the methods like interviews, participant observations, focus group discussion, narratives and case histories. The main instruments of the study are the structured questionnaires and open-ended interviews with the respective respondents into consideration. The study adopted self-administered methodology for data collection. Thus, more visited and sampled respondents had face to face discussion with feedback filled out on the questionnaires. The researcher adopted an interactive approach rather than ‘question and answer session’ with the respondents to enhance the quality of collected data.

3.7. Research Instruments

This study used both primary and secondary data. Primary data was collected using questionnaires and interview guides and some of the secondary data were obtained from literatures.

3.8. Quantification of the required feedstock

Feedstock for biogas production that will supply the energy required for cooking and water heating per each of 5 households taken as pilot study, has to be obtained from human faeces and caw dung. Daily human faeces per capita is 1kg/day for adult and 0.4 kg /day for young ranging from 10 to 15 years old. The average is 0.7kg daily according to Molla, A. (2014) & Fergusen, T. (2006). It means that 25 people per each bio-digester plant considering 5 people per house will generate 0.7x25 kg/day; that is equal to 17.5 kg/day of faeces. Mass of caw dung to be incorporated on co-digestion system was to be determined based on difference in volume of biogas needed to supply the required energy for total residence, and volume of biogas that will be generated by human faeces from the same residence, using expression in eqation1.

$$\mathbf{G} = \mathbf{M_s} * \mathbf{TS} * \mathbf{d.o.m} * \mathbf{W_b} \qquad \textbf{(Eq.1)}$$

Where: **G =**Daily biogas production rate

$\mathbf{M_s}$ = Mass of the substrate (kg)

TS = Mass of the total solid (% of Ms)

d.o.m = Dry organic matter (% of TS), $\mathbf{W_b}$ = Specific biogas production rate (m^3/kg of d.o.m)

The average specific gas production (W_b) of human faeces is 0.44 m^3/kg of dry organic matter, (Table 7), and Dry Matter content (TS) in the human faeces account for 15-35 % of total mass with which 80-92% of that is organic matter (Colon.J., et al.,2015 & Andriani,D.et al.,2015). For caw dung, average specific gas production is 0.24 m^3/kg of dry organic matter, (see Table 7), whereby Dry Matter (TS) content is 7-20% of the total mass with which dry organic matter account for 65-85% in average according to (Andriani, D.et al.,2015 & M. Audu, et al., 2013).

3.9. Design of a co-digestion bio-digester plant

For designing, the average daily energy needs for cooking and water heating per each of 5 households, as sample study per system, had to be quantified. This biogas has to be provided by the fact that it satisfies all the energy need for cooking and water heating in the total residence. This study adopted the hemispherical fixed dome digester among the others, due to its various advantages such as: Simple design, simple maintenance with no moving part, no potential of rusting, long lifespan of more than 20 years and low set-up costs.

3.9.1. An overview about a fixed dome digester

Waste matter is fed into the digester where it collects and is broken down, producing biogas which is stored in the gas holder part of the hemispherical digester. As the pressure of biogas increases the more the volume of slurry which is displaced into the displacement tank or compensation chamber. Excess slurry from the displacement tank will be removed, dried or composted and used for fertilizer or will overflow into a sewage outlet or slurry/ composting bed. Biogas is removed from the gas holder and can be used for cooking, lighting and heating as detailed. The fixed dome digester is commonly known as the 'Chinese' design and can be used in small scale (household) as well as on the large scale (community) systems. Figure13 bellow shows a fixed dome digester with a flat bottom.

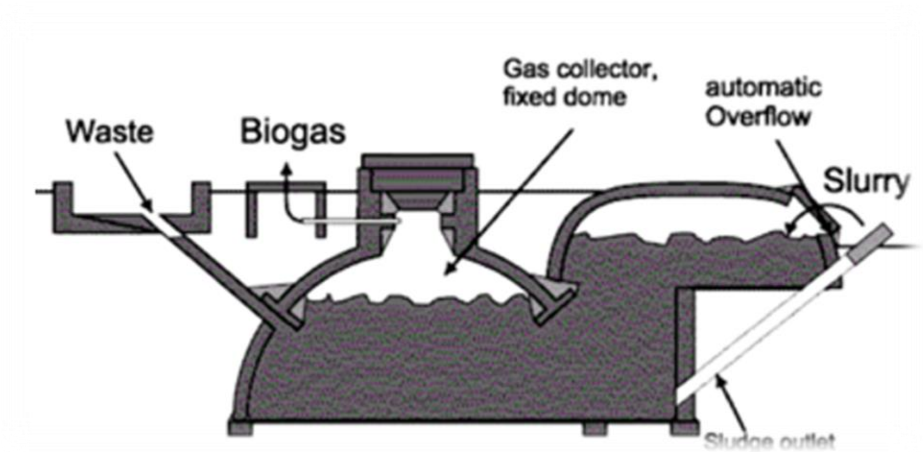


Figure 13. Hemispherical Fixed dome digester with flat bottom (Molla, A.,2014)

Construction of a fixed dome biogas plant, consists of an underground digester (usually flat/bowled based with a hemispherical top) covered with earth up to the top of the gas holder so as to offset the gas pressure. The plastic pipes or masonry tunnels provide the inlet/outlet for the digester. Bricks and the mortar are used to create the structure, the inside of which must be rendered and coated in waterproof and gas-proof coating.

3.9.2. Sizing of the plant parameters

Regardless of the type of digester there are some key parameters which need to be ensured a good design during this procedure. Figure 14 outlines these parameters

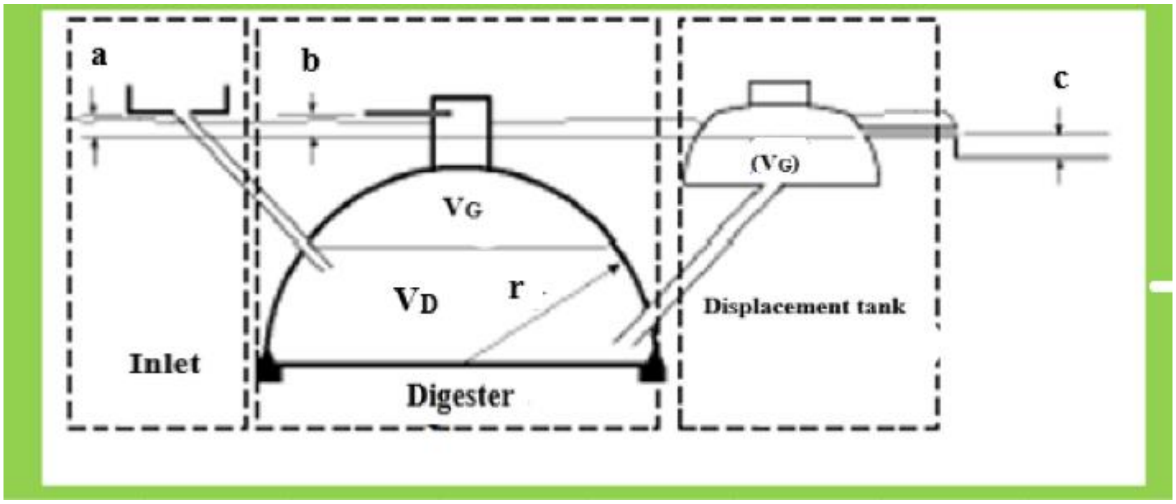


Figure 14. Schematic of digester parts and parameters

According to OXFAM, (2011), the parameters:

a= Height of inlet relative to slurry overflow outlet (> 0.3m)

b= Height of the gas outlet relative to the slurry overflow outlet (> 0.1m)

c= Height of slurry overflow outlet relative to the height of slurry drying bed/ compost area or sewage outlet (large enough to prevent backwash into digester, > 0.35m)

i. Digester and gas holder volume

Size of the digester largely depends on the amount of waste to be added. Digester shape should enable a minimum surface area: volume ratio to be reached to reduce heat loss and construction costs. The flat bottom for this hemispherical digester was considered. Calculation of the required digester volume **(V_D)** uses the Equation 2 below:

$$\mathbf{V_D = V_B * HRT} \qquad \textbf{(Eq.2)}$$

Where:

V_D = Volume of digester (m^3)

V_B = Volume of biomass added per day or organic loading rate (m^3/day)

HRT = Hydraulic retention time require (days)

The hemispherical fixed dome digester, (figure 15), consists of digester volume that is volume under the low slurry level (LSL), gas storage volume between the lower slurry level (LSL) and high slurry level (HSL) and 20% of gas storage volume known as safety factor or dead volume up the high slurry level. Dead volume is required however in order to accommodate the floating layer on the top of the slurry. In addition, when gas produced is less than nominal production during cold season or when gas is slowly leaking, the higher slurry level can rise up to the overflow level. For that reason, the total plant used for dimensioning should be higher than the plant size range. And the sum of gas storage volume and dead volume constitute the maximum gas holder volume of bio- digester plant.

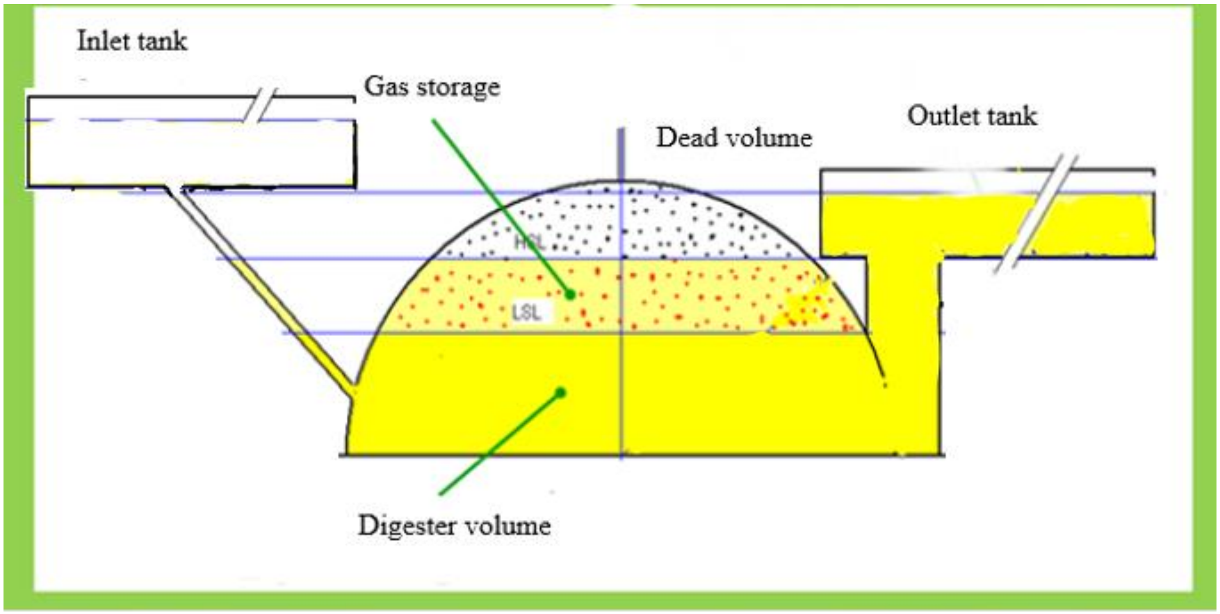


Figure 15. Hemispherical fixed dome digester Plant layout (Adopted from SNV)

According to TERI (1987), a fixed share of the maximum amount of daily gas generated at least 60% is kept in storage and only 40% has to be consumed. Therefore, gas storage volume (**V_G**) has to be:

$$\mathbf{V_G = 0.6G} \qquad \textbf{(Eq.3)}$$

$$\mathbf{V_{Gmax} = V_G + 0.2V_G} \qquad \textbf{(Eq.4)}$$

Where:

V_G= Gas (holder or storage) volume (m^3)

G = Daily gas production rate (m^3/day)

V_{Gmax} = Gas (holder or storage) volume with safety factor of 20% (m^3)

And hence, the design combines digester volume (**V_D**) with gas holder volume (**V_{Gmax}**) to give the total plant volume (**V_H**) as:

$$\mathbf{V_H = V_D + V_{Gmax}} \qquad \textbf{(Eq.5)}$$

ii. Geometric computation of bio- digester plant parameters

A. Computation of digester height and diameter

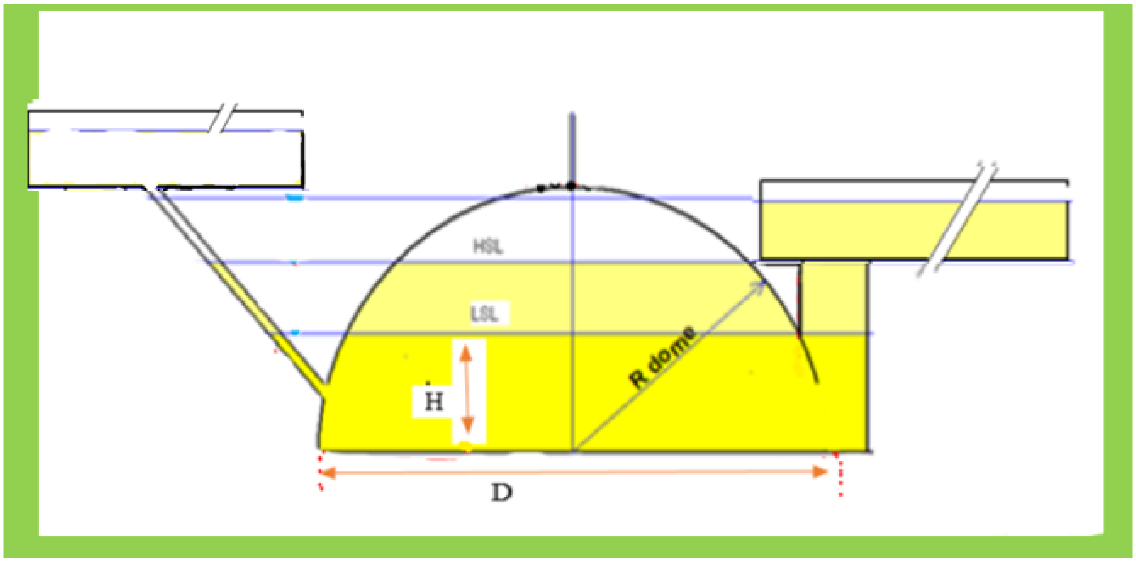


Figure 16.Digester parameters

The cylindrical portion of the hemispherical fixed dome digester is volume under the low slurry level known as slurry active volume or digester volume (**V_D**)**,** it is numerically defined by the Equation 2 as shown above**.** This volume part of digester plant can also be expressed geometrically by the relation in Equation 6 bellow:

$$\mathbf{V_D} = \left(\frac{\pi}{4}\right) * \mathbf{H} * \mathbf{D}^2, \qquad \textbf{(Eq.6)}$$

Due to TERI (1987) assumptions, **D** is equal to **2H** by approximation. Hence,

$$\mathbf{V_D} = \left(\frac{\pi}{4}\right) * \mathbf{4H}^3, \text{ or } \mathbf{H} = \left(\frac{\mathbf{V_D}}{\pi}\right)^{\left(\frac{1}{3}\right)} \qquad \textbf{(Eq.7)}$$

$$\text{Therefore, } \mathbf{D} = 2\left(\frac{\mathbf{V_D}}{\pi}\right)^{\left(\frac{1}{3}\right)} \qquad \textbf{(Eq.8)}$$

Where:

D= Diameter of digester (m)

H= Height of digester (m)

V_D = Digester volume or active slurry volume (m^3)

Thus, digester height (**H**) and diameter (**D**), (figure 16), can be obtained knowing the value of digester volume (**V_D**) from Equation 2.

B. Computation of the dome dimensions

This calculation serves to find the height of gas holder volume or height of the lower slurry level (LSL) from the top of dome, as well as dome radius, (figure 17).

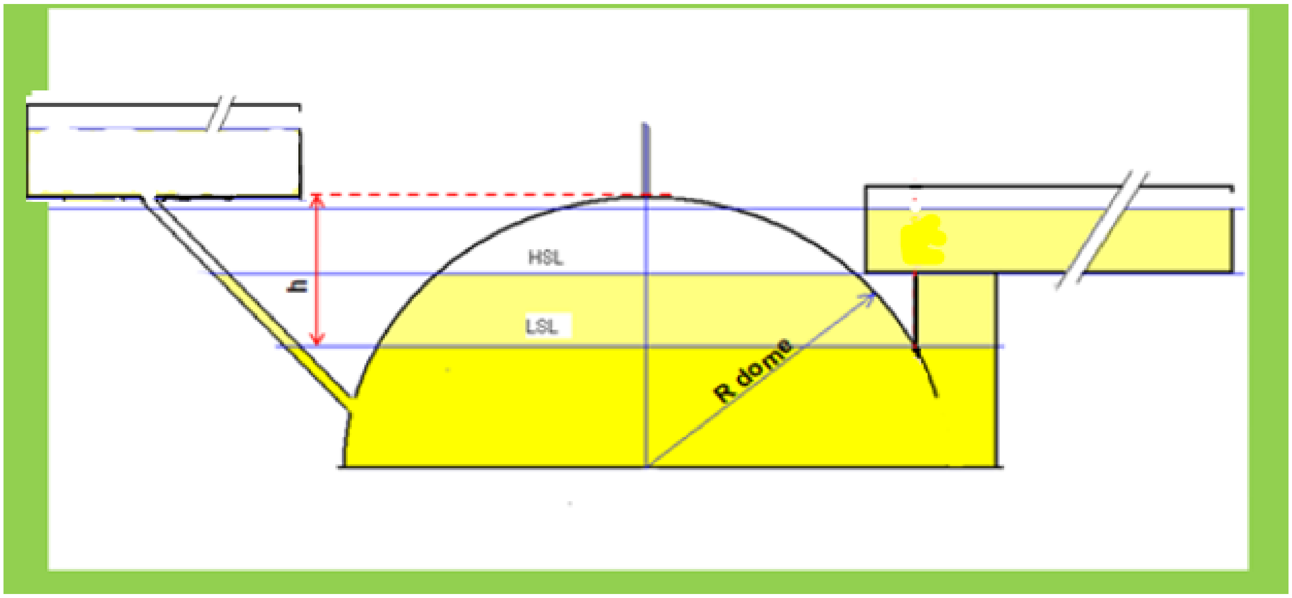


Figure 17.Geometric dimensions of the dome

Geometric expression of the dome volume (gas holder volume) is given by the relation in Equation 9 as:

$$V_{Gmax} = \left(\frac{\pi}{6}\right) * h * \left(3\left(\frac{D}{2}\right)^2 + h^2\right) \qquad \textbf{(Eq.9)}$$

Based on the SNV bio-digester calculator, (2014) and (OXFAM, 2011), for hemispherical fixed dome digester, dome radius or radius of the gas holder volume is expressed by:

$$R\ \text{dome} = \left(\frac{3V_H}{2\pi}\right)^{\left(\frac{1}{3}\right)} \qquad \textbf{(Eq.10)}$$

Where: **R=** Dome radius (m)

V_H = Total volume of hemispherical fixed dome plant (m^3)

h = Dome /gas holder height (m)

D = Digester diameter (m)

V_{Gmax} = Gas holder volume (m^3)

Thus, dome height (**h**)and radius (**R**) can be obtained knowing the value of digester diameter (**D**) from Equation 8 and gas holder volume ($\mathbf{V_{Gmax}}$) from Equation 4 and total plant volume($\mathbf{V_H}$) from Equation 5.

C. Estimation of the slurry displacement parameters inside digester

Selection of the value of digester diameter (**D**) depends upon gas utilization pattern. With the fact that gas holder volume ($\mathbf{V_G}$) has to be 60% of the daily gas production (**G**) according to TERI (1987), therefore, the variable gas storage volume ($\mathbf{V_{sd}}$) account for 40%. And this can numerically be expressed as:

$$\mathbf{V_{sd}} = 0.4\mathbf{G} \qquad \textbf{(Eq.11)}$$

Which is geometrically defined as $\mathbf{V_{sd}} = \left(\frac{\pi}{4}\right) * \mathbf{D^2} * \mathbf{d}$ **(Eq.12)**

Where:

D= Diameter of digester (m)

d= Slurry displacement inside digester (m)

Vsd = Variation in gas storage volume (m^3)

From Equation 6, it was shown that $\mathbf{V_D} = \left(\frac{\pi}{4}\right) * \mathbf{H} * \mathbf{D^2}$**,** which implies that:

$$\left(\frac{\pi}{4}\right) * \mathbf{D^2} = \frac{\mathbf{V_D}}{\mathbf{H}} \qquad \textbf{(Eq.13)}$$

Hence, equations 12 and 13 give $\mathbf{V_{sd}} = \left(\frac{\mathbf{V_D}}{\mathbf{H}}\right) * \mathbf{d}$ **(Eq.14)**

It means that, $\mathbf{d} = \frac{\mathbf{V_{sd} * H}}{\mathbf{V_D}}$ **(Eq.15)**

Substituting the value of **Vsd** from equation 11 in equation 15, slurry displacement will be given by: $\mathbf{d} = \frac{(\mathbf{0.4}\ G * H)}{V_D}$ **(Eq.16)**

Knowing the value of daily gas production (**G**) from Equation 1, digester height (**H**) from Equation 7 and digester volume ($\mathbf{V_D}$) from Equation 2, we can find the value of daily slurry displacement (**d**) inside digester.

C. Computation of the slurry displacement in the Outlet Tanks

Maximum pressure exerted on gas inside digester is equal to the pressure of the water (slurry) column above the lowest slurry level in the outlet tank. According to TERI (1987), this pressure is normally selected to be 0.85m water gouge as a safe limit for brick/ concrete domes.

Thus, $\mathbf{X} + \mathbf{d} = 0.85$ **(Eq.17)**

Where: **X**= Slurry displacement in the outlet tank (m)

d = Slurry displacement inside digester (m)

Knowing the value of slurry displacement (**d**) in digester from Equation 16, the slurry displacement (**X**) in the outlet tank will be calculated as:

$$\mathbf{X} = \mathbf{0.85} - \mathbf{d} \qquad \textbf{(Eq.18)}$$

D. Computation of the length (L) and Breadth or width (B) of the inlet and outlet tanks

There is no specific criterion with regard to the choice of the shape of cross– section of inlet and outlet tanks, but generally a rectangular shape with **L =1.5B** is preferred TERI (1987)**.**

For case when inlet and outlet tanks have identical shapes, volume of slurry displaced downwards inside the digester is equal to the total volume of slurry displaced upwards in the inlet and outlet tanks**.** Thus,

$$\mathbf{2(L * B * X) = V_{sd}}, \qquad \textbf{(Eq.19)}$$

Therefore, by substituting **L**=1.5**B**, we get $\mathbf{2(1.5B) * B * X = V_{sd}}$

Then, $\mathbf{B} = \left(\frac{\mathbf{V_{sd}}}{\mathbf{3X}}\right)^{\frac{1}{2}}$ **(Eq.20)**

Where:

L = Length of inlet and outlet tanks (m)

B = Breadth of inlet and outlet tanks (m)

X = Slurry displacement in inlet and outlet tanks (m)

The values of inlet and outlet tanks breadths (widths) and lengths can be calculated from Equation 20, knowing the value of storage volume variation (**Vsd**) from Equation 11 and Slurry displacement in inlet and outlet tanks from Equation 18. See figure 18 for rectangular shape inlet and outlet tanks.

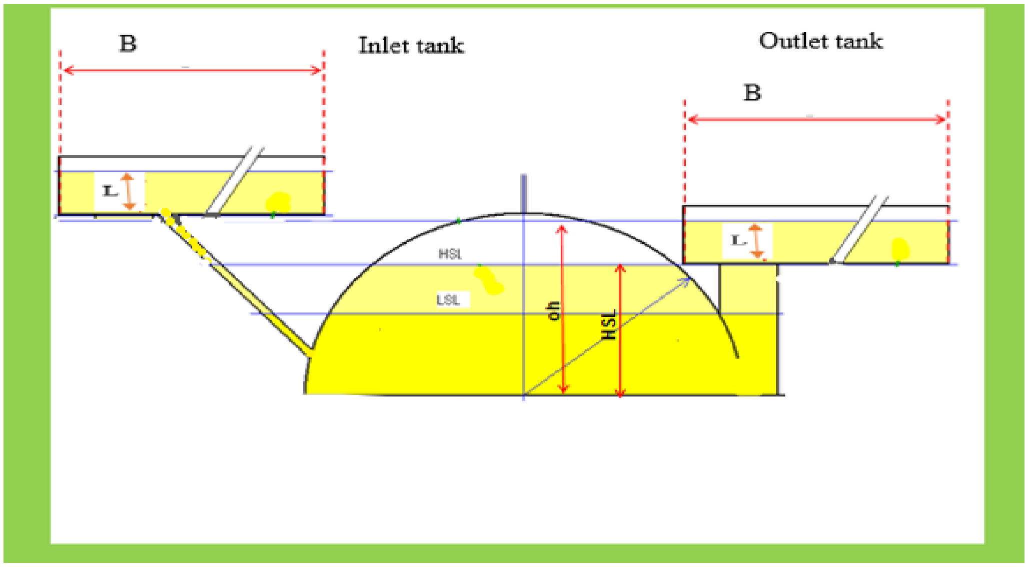


Figure 18.Dimensions of inlet and outlet tanks

Estimation of overflow and pressure height

Overflow height determines the maximum pressure in the plant, that is the extent to which the slurry can reach the gas dome pipe and dimension of compensation chamber, (see figure 19), for these parameters.

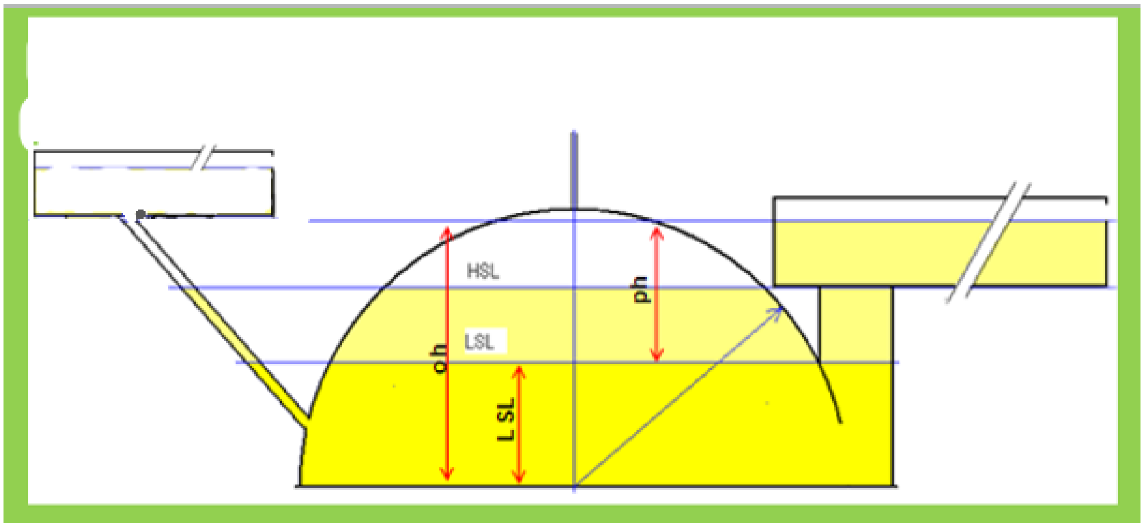


Figure 19. Overflow height and pressure height estimation

The overflow height (**Oh**) has to be positioned under the bottom of the dome pipe in order to avoid slurry from reaching the bottom of the gas dome pipe.

Slurry can reach the bottom of the dome in the case where plants are leaking gas, for temperature reason or when gas production is significantly lower than gas consumption over a prolonged period of time.

For a medium sized plant, the overflow height is positioned at 5 cm under the top of the dome.

It means that, **Oh = (R- 0.05)** (**Eq.21**)

Where: **Oh** = overflow height (m)

R = is dome radius (m)

While, pressure height (**Ph**) is the maximum pressure that the installation can produce. This maximum pressure is limited by LSL. When pressure increases to the point whereby the LSL is pushed down further below outlet pipe level, biogas will escape through the compensation chamber. The pressure height is given by the difference between overflow height (**Oh**) and LSL.

Therfore, **Ph = Oh – H** (**Eq.22**)

Where: **Oh** = Overflow height (m)

H = Digester height (m)

Ph= Pressure height (m)

E. Estimation of inlet floor and inlet pipe

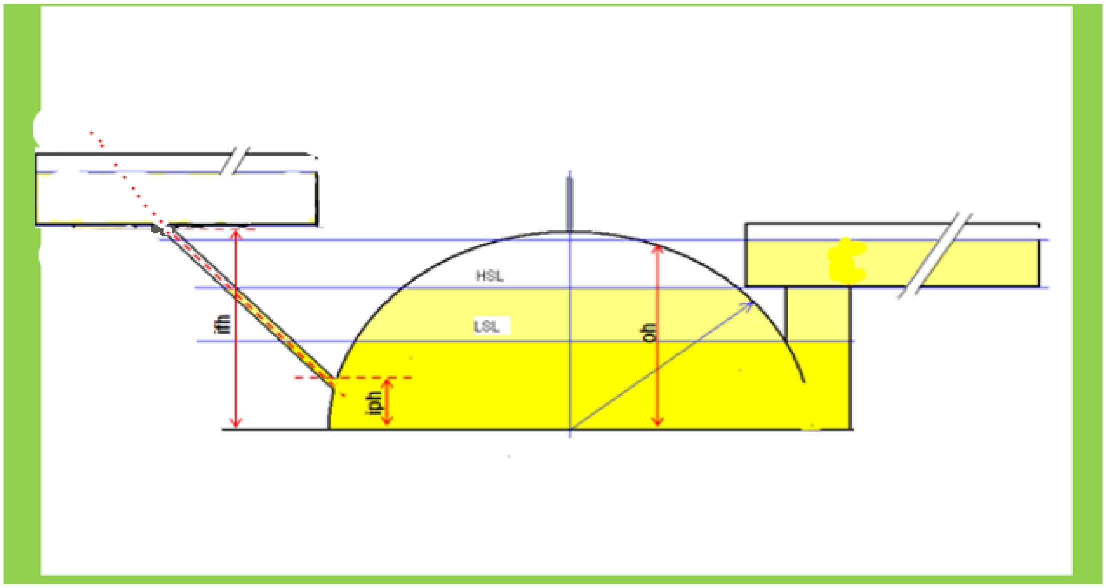


Figure 20.Inlet floor and pipe dimensions

Typically, the inlet pipe height (**iph**), (see figure 20), has to be about 0.30 m above the digester floor to avoid reflux, and the inlet floor height (**ifh**) should be higher than the overflow height (**Oh**). For a medium plant size, the inlet flow height has to be 0.15 m higher than overflow height according to SNV bio-digester calculator, (2014). Infact, the inlet pipe height can not be too close to the digester floor to prevent the obstruction by debri. And inorder to avoid the biogas from escaping through the inlet pipe such as toilet connection, the top of the inlet entering the dome must be below the LSL. In addtion, the inlet/ pipe layout must allow entering of the long stick in case of pipe blockage. The inlet flow height is numerically express as:

$$\mathbf{ifh = Oh + 0.15 \quad (m)} \qquad \textbf{(Eq.23)}$$

3.9.1. The plant's cost analysis

The economic evaluation of a relative centralized anaerobic plant size largely depends on the output of the facility. These outputs consist of the entire energy production and digestate. A complete cost package of the components above has been established in comparison with the inputs to be able to justify economically. The difference between the gross outputs value with the inputs will help to draw the distinct state of the economics status of the plant. It informs the user(s) of the financial position of the investing in such project. Aside from the technical conditions that are involved in building a biogas plant, the cost remains a backbone of the entire project. The financial evaluation helps to identify the profit margins accured from the complete operation cycle of the biogas plant. Financial waivers from Government authorities on tax exemption if applicable, subsidies and above all the market price have a cumulative effect on the outcome.

Two cost parameters are the most influential factors which are the capital expenditure (CAPEX) and operating expenses (OPEX). The breakdown of the CAPEX covers the investment cost of putting a biogas plant. According to Akoore. A.,(2018), the capital cost, however, is incorporated into total plant cost (TPC).While, OPEX is referred to as short-term expenses or day-to – day expenduture necessary to keep the business running. Nevertheless, the defining economic variables are the net present value (NPV), benefit to cost ratio, internal rate of return (IRR) and simple payback time. The NPV in simple terms is the sum of all year's discounted after- tax cash flow. The higher the NPV, the higher is the profit margin of the project.

In other words the NPV is described as the difference between the present value of cash inflow and present value of cash outflow, and is given by:

$$\mathbf{NPV} = \sum_{t=1}^{T} \left(\frac{C_t}{(1+r)^t} - C\right) \qquad \textbf{(Eq.23)}$$

Where:

$\mathbf{C_t}$ = Net cash flow during the period t

C=Total initial investment

r= Discount rate

t= number of periods (years)

If **NPV** < 0, project is not economically viable

If **NPV** > 0, project is economically viable

The payback time is the period duration required to recover the amount of money invested in the project.

And the cost to benefit ratio $= \frac{\text{Initial Investiment}}{\text{Annual Cash inflow}}$ **(Eq.24)**

Internal rate of Return $= \frac{\text{Annual cash flow}*100}{\text{initial investment}}$ **(Eq.25)**

By the mean of RETSCREEN software all those financial parameters have be determined and presented in the findings of the study.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0. Introduction.

This section presents the results for data analysis and discussion of the findings. The section has results on the family size for the study sample, the energy alternatives and relative consumptions for cooking and heating water, information on the incomes level and the size of bio-digester plant with all parameters that have to match the energy requirement for the pilot study.

4.1. Size of the Family

The results on the family size indicated that 10 % of the households that participated in the study had members that are less than 3, 59.1% had 3 to 5 members, and 30% had 6 to 12 members. This survey was simply based on for assumed family size that will match the design of a co-digestion biogas system, in the study the average of 5 people per household was chosen to be. The results of survey are presented by figure 21.

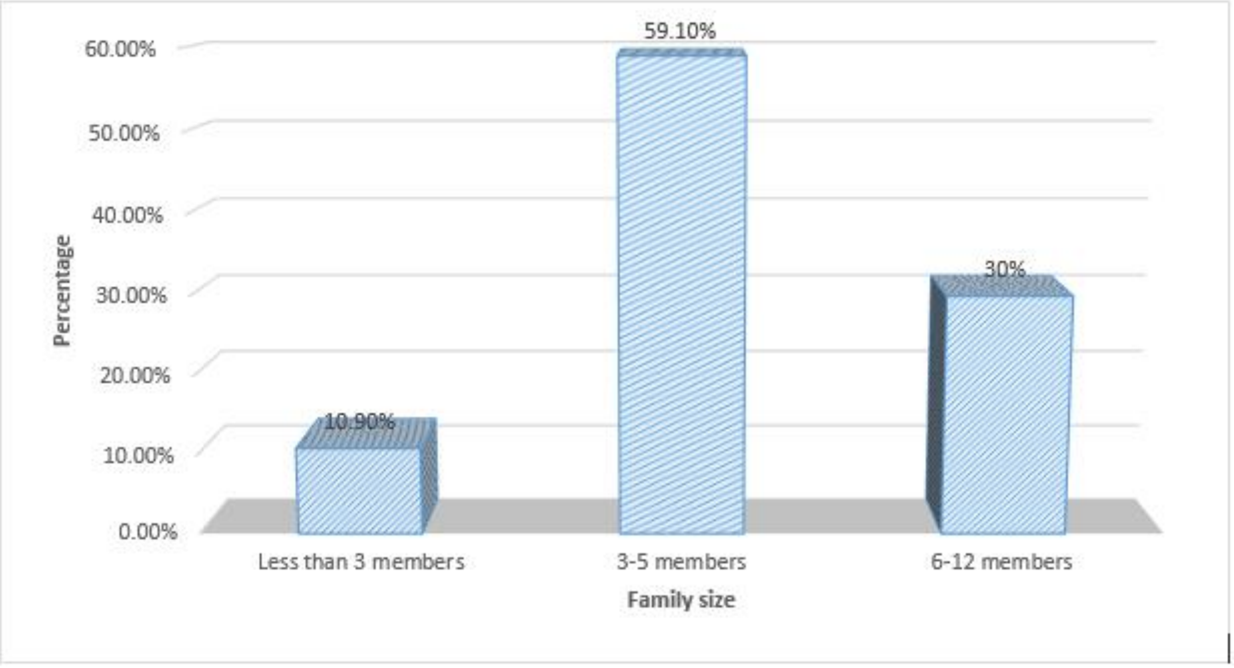


Figure 21.Family size for respondents

4.2. Sources of energy for cooking and heating water in the pilot study

In order to obtain the energy needs, questionnaire acquiring alternatives energy source for cooking and water heating, as well as the average monthly energy consumption in households of Gicumbi District was given to the respondents. The results of this survey is presented by the figure 22 and Table 11 below.

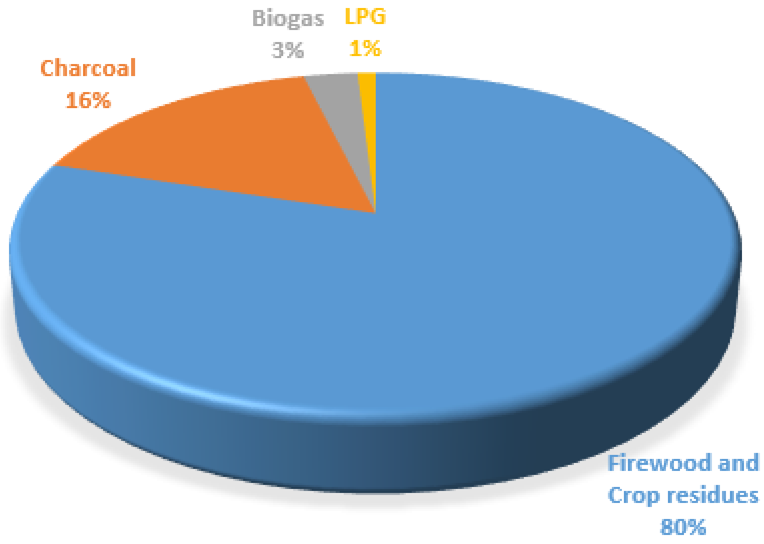


Figure 22.Alternative sources of energy for pilot study.

For 210 of respondents, 168 of them, that account 80%, use firewood and crop residues for cooking and heating water,34 of them that is 16% use charcoal, 6 use biogas from NDBP that is 3% and 2 of them that is 1% use LPG. In order to depicture the energy consumption according to fuel used, Table 11 below is presented.

Table 11. Energy consumption rate for cooking and heating water

No.	Fuel type for cooking and heating water	Average consumption per day per household	Average consumption per day per total residence	Amount per month per household	Total consumption per month per total residence	Unit price in RWF	Total Price in RWF
1	Charcoal	1.2kg	5.8 kg	35kg	175kg	300	52,500
2	Dung cake	0	0	0	0	0	0
3	Firewood and crop residues	Unspecified	Unspecified	Unspecified	Unspecified	unspecified	-
4	Biogas	Unspecified	Unspecified	Unspecified	Unspecified	unspecified	-
5	LPG	0.6kg	3kg	18kg	90kg	1,083	97,500
6	Electricity	0	0	0	0	0	0
7	Others	No value	No value	No value	No value	No value	No value

It was found that firewood and crop residues are the most dominant source of energy used for cooking and heating water in households of Gicumbi district (80 %), followed by charcoal (16 %). The direct quantification of firewood consumption seems complicated, because in some cases households use residues some that the monthly estimation was difficult for them. In addition, the information about the origin of the wood was not available, whether it is collected or purchased, and whether households will use this quantity throughout the year. It was quite possible that households stock up on wood but do not use it every day, in which case any quantification may be an over-estimation. Also according to the survey done by EUEI (2009), Kigali and Western Province of Rwanda use the most wood ranging from 2.4-2.6 kg per person per day, and in the other provinces it is 1.4-1.6 kg per person per day. These includes Northern Province where is Gicumbi district. The average annual per capita firewood consumption over the country was estimated at 60kg. Therefore, for certainty of the study while quantifying the monthly energy consumption in households, the research considered the households that used only charcoal for cooking and heating water at least in the last 6 months.

The average monthly charcoal consumption per total residence was found to be 175kg, that implies a daily consumption of 5.8 kg. According to the literature, (Table 9), 1 m^3 of biogas is equivalent to 2kg of charcoal. Therefore, the daily energy needs per five households that has to be supplied by 5.8 kg of charcoal per day is equivalent to 2.9 m^3 of biogas.

According to TERI (1987), for the optimum design of a bio-digester plant the daily gas consumption must be at most 40% of the daily gas production (**G**) from the feedstock. It means that, 2.9 m^3 of biogas required for the total residence per day is 40% of the total daily gas production that the plant is designed for. Then, the plant is designed for $\frac{2.9*100}{40}$ m^3 ; which is 7.25 m^3 of biogas per day.

Using expression in the equation 1, where daily gas production from the feedstock

G= M$_s$*TS*d.o.m*W$_b$, $\left(\frac{m^3}{day}\right)$

- For human wastes in study.

M_s =17.5kg/day; TS = 25%; d.o.m= 90%; W_b = 0.44 m^3/kg

here, biogas that will be collected from human faeces of 25 people per bio-digester plant is:

G_{human} = 17.5kg/day*(0.25) *(0.9) * (0.44m^3/kg)

= 1.7325 m^3/day

Hence, 7.25 m^3- 1.7325 m^3 = 5.52 $m^3$of biogas per day will be generated from caw dung in addition.

where, G_{human}= daily gas production from human faeces (m^3).

From the same expression of equation1; mass of caw dung that is responsible to generate this volume of gas can be determined having the value of daily gas needed from it,

TS= 13.5%; d.o.m=75%; W_b = 0.3 m^3/kg for caw dung**.** Therefore, mass of caw dung is:

$$\mathbf{M_{s,caw}} = \frac{\mathbf{G_{caw}}}{(\mathbf{TS*d.o.m*Wb})} \quad \textbf{(kg)} \qquad \textbf{(Eq.26)}$$

$$= \frac{5.52\text{m}^3}{0.135*0.75*\frac{0.3\text{m}^3}{\text{kg}}}$$

= 182 kg of caw dung per day

Where**:** $\mathbf{M_{s,caw}}$**=** total daily mass flow of caw dung (kg)

$\mathbf{G}_{\text{caw}}$ = daily gas production rate from total caw dung (m^3)

Biogas required to supply the daily energy demand for each of 5 households will need 17.5kg of human faeces and 182 kg of caw dung per day.

4.3. Estimation of the digester, gas holder and the total plant volume

Digester volume is given by expression in Equation 2**,** $\mathbf{V_D = V_B * HRT}$ $(\boldsymbol{m^3})$

The volume flow rate ($\mathbf{V_B}$) of the feedstock (human faeces and caw dung) is given by:

$$\mathbf{V_B} = \frac{\text{Total mass of human faeces}}{\text{Density of human manure}} + \frac{\text{Total mass of caw dung}}{\text{Density of caw dung}} \qquad \textbf{(Eq.27)}$$

With density of human manure equals to $\frac{1000\text{kg}}{\text{m3}}$ (Molla, A.,2014) and $\frac{930\text{kg}}{\text{m3}}$ for caw dung , according to Akoore, A., (2018).

Therefore, $V_B = \frac{17.5kg}{\frac{1000\text{kg}}{\text{m3}}} + \frac{182\text{kg}}{\frac{930\text{kg}}{\text{m3}}}$

$V_B = 0.0175 \text{ m}^3 + 0.1957 \text{ m}^3$

$= 0.2132 \text{ m}^3$ per day

Based on the SNV calculator, (2014) and (Molla, A.,2014), in order to achieve the required solid concentration ranging between 7% to 8%, the equal amount of water has to be added, as 1:1 dilution ratio. It means that the total volume flow rate $V_B = 0.2132 \text{ m}^3 + 0.2132 \text{ m}^3$

$= 0.4264 \text{ m}^3$ of feedstock per day**.**

The hydraulic retention time of 60 days is assumed as according to SNV Rwanda report of 2005, climate of Rwanda varies between 15°C to 30°C that is considered as a moderately warm climate.

Hence, Digester volume $= 0.4264 \frac{\text{m3}}{\text{day}} * 60\text{days}$

$V_D = 25.6 \text{ m}^3$

The maximum value of gas holder volume **is** $V_{Gmax} = 0.6G + 0.2V_G$, (Equation 4).

Hence, $V_{Gmax} = (0.6 * 7.25 \text{ m}^3) + \left(0.2 * (0.6 * 7.25\text{m}^3)\right)$

$= 5.22 \text{ m}^3$

The plant will have a digester of 25.6 m^3 and gas holder of 5.22 m^3**.** And the total plant volume is $\mathbf{V_H = V_D + V_{Gmax}}$, see equation 5**.**

$= 25.6 \text{ m}^3 + 5.22 \text{ m}^3$

$= 30.82 \text{ m}^3$; which is about 31m^3.

4.4. Estimations of other plant parameters

4.4.1. Digester height and Diameter

Digester height is expressed as $\mathbf{H} = \left(\frac{\mathbf{V_D}}{\boldsymbol{\pi}}\right)^{\left(\frac{1}{3}\right)}$**, (**Equation 7)**.**

Hence, $\mathbf{H} = \left(\frac{\mathbf{25.6}\, \boldsymbol{m^3}}{\left(\frac{\mathbf{22}}{\mathbf{7}}\right)}\right)^{\frac{\mathbf{1}}{\mathbf{3}}}$

= 2m

According to TERI (1987), D= 2H. It means that digester diameter is D= 4m

4.4.2. Dome dimensions

i. Dome or gas holder height

From Equation 9, gas holder volume is expressed as $\mathbf{V_{Gmax}} = \left(\frac{\pi}{6}\right) * \mathbf{h} *(\mathbf{3}\left(\frac{D}{2}\right)^{\mathbf{2}} + \mathbf{h^2}))$

By solving this cubic polynomial equation for **h**,

$$\left(\frac{\boldsymbol{\pi}}{\mathbf{6}}\right) * \mathbf{h^3} + \left(\frac{\mathbf{3\pi}}{\mathbf{24}}\right) * \mathbf{D^2} * \mathbf{h} - \mathbf{V_{Gmax}} = \mathbf{0}$$

Replacing the values of $\mathbf{V_{Gmax}}$ and **D**, through excel calculator the value of the dome height was found to be:

h= 0.75474 m, which is about 0.75m.

ii. Dome or gas holder radius

Dome radius was expressed by relation in the equation 10 as mentioned above,

$\mathbf{R} = \left(\frac{\mathbf{3V_H}}{\mathbf{2\pi}}\right)^{\left(\frac{\mathbf{1}}{\mathbf{3}}\right)}$

$= \left(3 * \frac{30.82\mathrm{m}^3}{2\pi}\right)^{\frac{\mathbf{1}}{\mathbf{3}}}$ **.** Hence, dome radius R = 2.45 m.

4.4.3. Slurry displacement inside digester, as well as in inlet and outlet tanks

Slurry displacement inside digester is expressed by the relation in equation 16,

$\mathbf{d} = \frac{\mathbf{(0.4\ G*H)}}{\mathbf{V_D}}$

$= \frac{0.4*7.25\mathrm{m}^3*2\mathrm{m}}{25.6\mathrm{m}^3}$; d=0.23m

Slurry displacement in inlet and outlet tanks is expressed by the relation in Equation 18,

$X = 0.85 - d$, $X = 0.85\text{ m} - 0.23\text{m}$

$= 0.62\text{m}$

4.4.4. Length (L) and Breadth or width (B) of the inlet and outlet tanks

Breadth of both inlet and outlets tanks is expressed by expression in Equation 20,

$$\mathbf{B} = \left(\frac{\mathbf{V_{sd}}}{\mathbf{3X}}\right)^{\frac{1}{2}}$$

$$= \left(0.4 * \frac{7.25\text{m}^3}{3 * 0.62\text{m}}\right)^{\frac{1}{2}}$$

$= 1.23\text{m}$

Inlet and outlet tanks length is expressed as L=1.5B.

Hence, L= 1.5 * 1.23m

= 1.845m

4.4.5. Overflow and pressure heights

Overflow height is given by the expression in Equation 21

Oh = (R- 0.05)

= 2.45m-0.05m, Oh=2.4m

And pressure height Ph = Oh-H

= 2.4m-2m

= 0.4m

It means that, the maximum pressure head that gas will exert on the low slurry level without escaping throughout the compensation chamber is 0.4m**,** that is also known as the maximum pressure that the installation can produce.

4.4.6. Inlet flow height, Inlet pipe height and High slurry level

Inlet flow height is express by equation 23, ifh= Oh+0.15

= 2.4m+0.15m

= 2.55m

Compensation chamber flow height which is equivalent to the High slurry level, Cfh= d +H

= 0.23m+2m

Cfh = 2.23m, and the inlet pipe height is assumed to be 0.3m.

The following figure 23 describes the physical parameters of the co-digestion bio-digester plant in this thesis work**.**

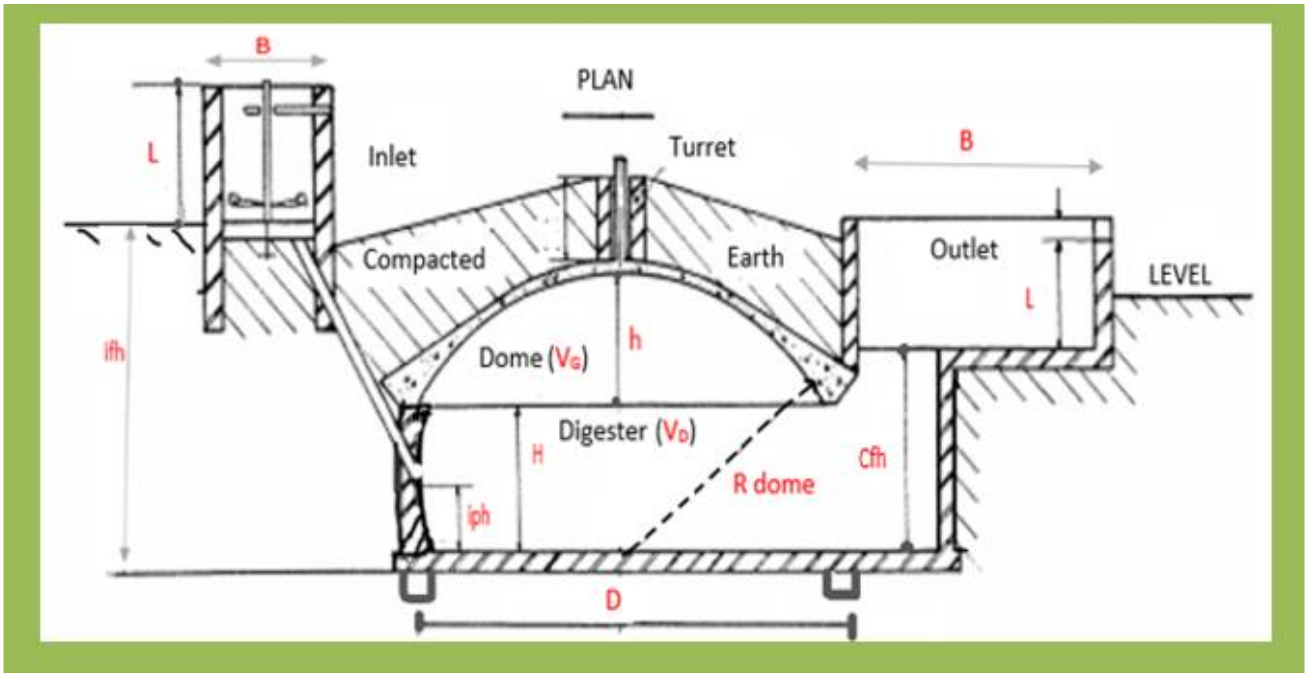


Figure 23.Plan of digester plant with all physical parameters

Table 12, summarizes they key parameters of the biogas digester plant that is designed relative to the survey of the energy needs for the residence into consideration from the pilot study.

Table 12. Bio-digester plant’s parameters with the respective values

Plant parameter	**Symbol**	**Value**	**SI unit**
Total plant volume	V_H	30.82	m^3
Digester volume	V_D	25.6	m^3
Gas holder volume	V_G	5.22	m^3
Digester diameter	D	4	m
Digester height	H	2	m
Dome radius	R	2.45	m
Dome height	h	0.75	m
Compensation chamber flow height	Cfh	2.38	m
Inlet and outlet tanks breadth	B	1.88	m
Inlet and outlet tanks Length	L	1.25	m
Inlet flow height	Ifh	2.55	m
Inlet pipe height	Iph	0.3	m
Slurry displacement inside digester	d	0.24	m
Slurry displacement in inlet and outlet tanks	X	0.61	m
Overflow height	Oh	2.4	m
Pressure head	Ph	0.26	m
Height of inlet relative to slurry overflow outlet	a	>0.3	m
Height of the gas outlet relative to the slurry overflow outlet	b	>0.1	m
Height of slurry overflow outlet relative to the height of slurry drying bed	c	>0.35	m

4.5. Bio-digester plant cost estimates

4.5.1. Financial Assumptions

The following financial assumptions were considered while determining the investment cost of the co-digestion bio-digester plant in the study.

- Investment subsidy given by the government 50% of the project's overall cost as well as for NDBP (SIBOMANA.J.P.,2018).
- 30% dept. ratio from the banks usually (SACCO and Bank Populaire) that uses to finance NDBP.
- Project lifespan is 20 years
- Operation and Maintenance cost per year (O&M) 2 % of initial investment
- Discount rate 10%
- Value – added tax (VAT) is 0%
- Money inflation rate 2%
- And 1% of annual contingencies

4.5.2 Estimation of investments and revenues for plant

According to the results from survey, it has been found that the monthly expenditure to buy charcoals for the pilot study was 52,500 Rwandan francs (RWF). This implies the annual expenditure of RWF 630,000 for buying charcoal. Therefore, RWF 630,000 or USD700 will be saved per year while using the biogas system designed in this study. In addition, the incomes also will be generated from selling or using the digestate or manure after biogas harvesting.

To quantify this amount of manure, that the system will generate daily,

Same assumption and approximate approaches were taken:

- ✓ The approximate values for biogas content which is about 65 % of $\mathrm{CH_4}$and 35% of $\mathrm{CO_2}$ in average as the most components of biogas products (Table 5) , and neglect other small portion of gases
- ✓ Gas are assumed to be ideal.

Hence, from this approximation the daily gas production that is 7.25 m^3 , the system is designed for, this approximately $\frac{\mathbf{7.25\ m^3 * 65}}{\mathbf{100}}$ **;** equal to 4.7m^3 or 4700 L of methane ($\mathrm{CH_4}$), and $\frac{\mathbf{7.25\ m^3 * 35}}{\mathbf{100}}$ **;** equal to 2.55 m^3 or 2550 L of carbon dioxide ($\mathrm{CO_2}$).

Infact, in the normal conditions of temperature (20^{oc}) and pressure (1atmosphere). 1 mole of either $\mathrm{CH_4}$ and $\mathrm{CO_2}$ assumed ideal occupies 22.4L of volume.

The maximum pressure on the gas inside digester has to be of 0.85m water gauge limit for bricks/concrete digester plant, according to TERI (1987).

With 0.85m water gauge = 0.082atm.

Ideal gas assumption implies that: PV=nRT, or PV/T= nR ; that is constant. **(Eq.28)**

Where: P= Pressure on gas (atm.)

V= volume of gas (L)

T= temperature inside digester (^{o}C)

n= number of moles

R= Ideal gas constant (KJ/kg K)

Hence, $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$; T_1=T_2.

$V_2 = \frac{P_1V_1}{P_2}$; Therefore, the volume of 1mole of either $\mathrm{CH_4}$ and $\mathrm{CO_2}$ in digester will be

$V_2 = 1atm.* \frac{22.4L}{0.082atm}$.

= 273.17 L/mole

Then, let compute the number of moles (**n**) that 4700 L of $\mathrm{CH_4}$ contains under this condition

$$\mathrm{n} = \frac{\mathrm{4700L}}{\frac{\mathrm{273.17L}}{\mathrm{mole}}}$$

= 17moles of methane ($\mathrm{CH_4}$).

And for $\mathrm{CO_2}$, $\mathrm{n} = \frac{\mathrm{2550L}}{\frac{\mathrm{273.17L}}{\mathrm{mole}}}$, $\mathrm{n} =$ 9 moles of carbon dioxide ($\mathrm{CO_2}$).

Also, 1 mole of $\mathrm{CH_4}$ has 16g of mass, which means that 17 moles weight:

$\mathrm{17\ moles} * \frac{\mathbf{16g}}{\mathbf{mole}}$ = 275g or 0.275 kg

And 1 mole of $\mathrm{CO_2}$, has 44g of mass, that implies that 9 moles weight:

$\mathrm{9moles} * \frac{\mathbf{44g}}{\mathbf{mole}}$ = 410g or 0.410 kg

Therefore, the total mass of feedstock that will be converted to biogas = 0.275kg + 0.410kg

= 0.686 kg of biogas per day

It means that only 0.686 kg of volatile solid (organic matter) among 4.7 kg in total will be converted into biogas per day under this condition and the rest of biomass will go out as digestate. Daily feeding of digester as mentioned above, account for 182kg of caw dung containing 80% of moisture and 17.5 kg of human faeces containing 75% of moisture in the average, (Table 7).

This implies that the dry matter (Total solid content) in the daily loading is:

$$\frac{\mathbf{182}\boldsymbol{kg}*\mathbf{20}}{\mathbf{100}} + \frac{\mathbf{17.5kg}*\mathbf{25}}{\mathbf{100}} = 40.8\text{kg /day of dry biomass.}$$

Hence, mass of digestate that will be generated from the plant per day =40.8kg-0.686 kg

= 40.1kg of digestate per day

Thus, the annual digestate (bio-slurry) production will be 14.636 tons/year. The following Table 13, contains the financial parameters based for evaluating the viability of plant in study.

Table 13.A comprehensive cost analysis of the bio-digester plant in the study

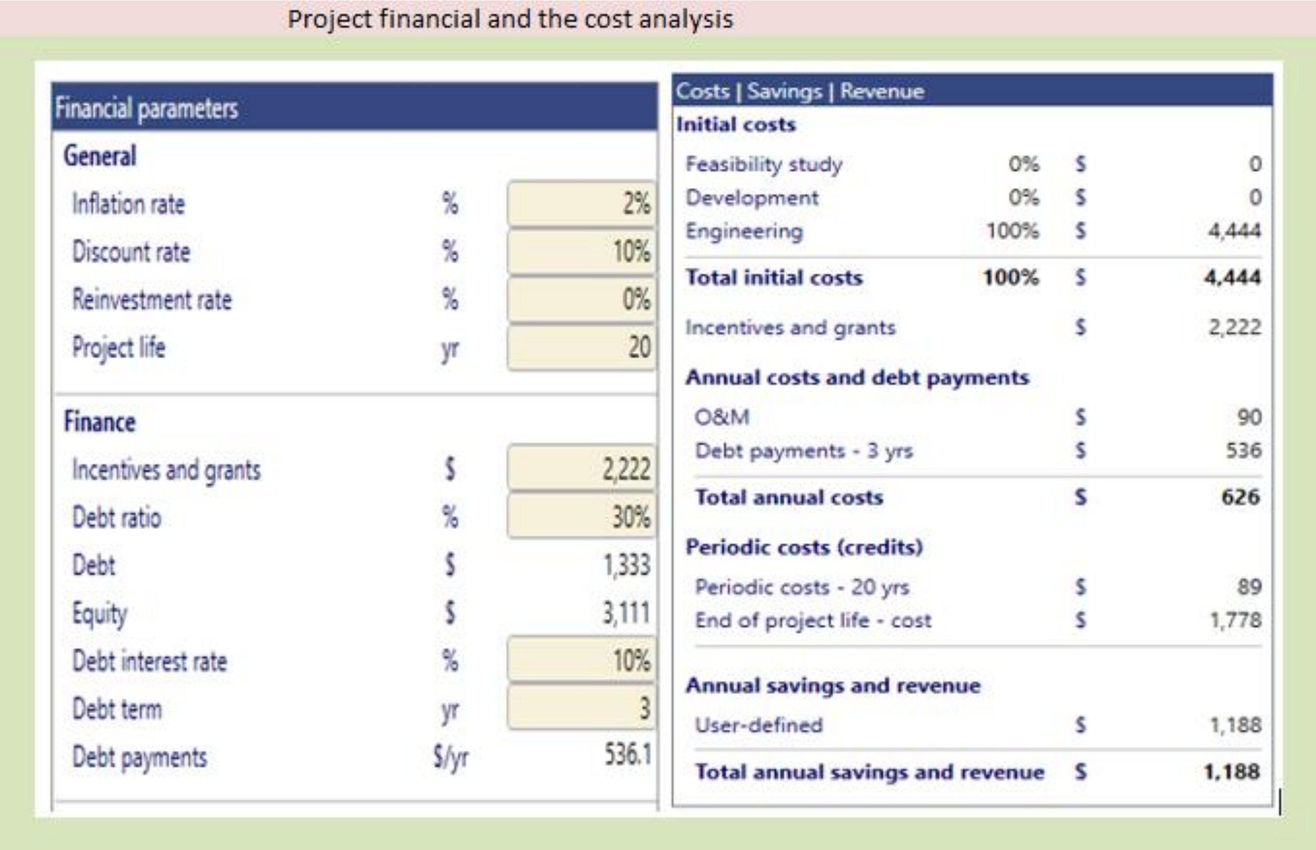
Cost	
Plant upfront cost	RFW4,000,000 or USD4444
O&M cost (2% of initial investment)	RWF80,000 or USD88.8
O&M for 20 years	RWF1,600,000 or USD1777.8
Total cost (20 years)	RWF5,600,000 or USD 6222
Benefit	
Equivalent amounts of charcoal saved per year	2100kg of charcoal or 60 bags
Money saved per year	RWF630,000 or USD700
Total manure produced per year	14636 kg
Money generated from selling manure or bio-slurry (RWF 30/kg)	RWF 439,095 or USD 488
Total annual cash flow in (Annual benefit)	RWF1,221,300 or USD1188

USD1 = RWF 900 (source: BNR)

The upfront cost for this plant was not quantified, but based on the experience of the Environment Management Officer of Gicumbi District who is in charge of domestic biogas dissemination through

NDBP in collaboration with Director of Agriculture and Natural resources unit, an approximate cost value was given to the plant size of 31m^3. This cost was given, relative to the costs of existing bio-digester plant sizes of RWF 630,000 (USD700) for 6 m^3; RWF 743,000 (USD825.5) for 8 m^3, and RWF 1,500,000 (USD1666.6) for 10 m^3. Table 14 bellow present the project's financial and cost analysis for this study.

Table 14. Project financial and cost analysis



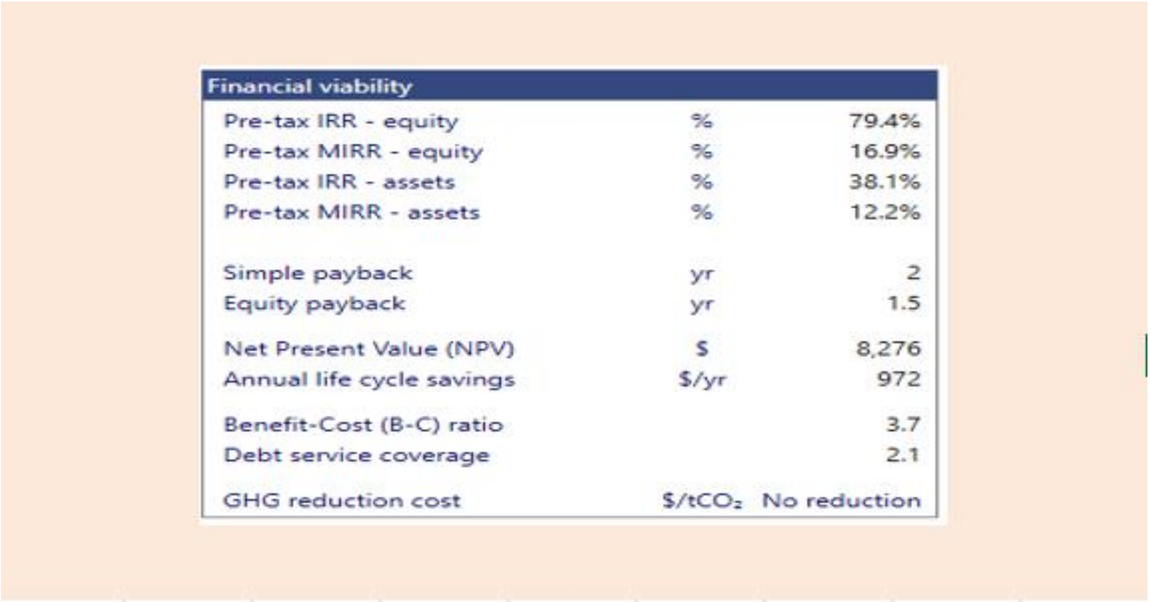
Project financial and the cost analysis

Financial parameters		
General		
Inflation rate	%	2%
Discount rate	%	10%
Reinvestment rate	%	0%
Project life	yr	20
Finance		
Incentives and grants	$	2,222
Debt ratio	%	30%
Debt	$	1,333
Equity	$	3,111
Debt interest rate	%	10%
Debt term	yr	3
Debt payments	$/yr	536.1

Costs | Savings | Revenue			
Initial costs			
Feasibility study	0%	$	0
Development	0%	$	0
Engineering	100%	$	4,444
Total initial costs	**100%**	**$**	**4,444**
Incentives and grants		$	2,222
Annual costs and debt payments			
O&M		$	90
Debt payments - 3 yrs		$	536
Total annual costs		**$**	**626**
Periodic costs (credits)			
Periodic costs - 20 yrs		$	89
End of project life - cost		$	1,778
Annual savings and revenue			
User-defined		$	1,188
Total annual savings and revenue		**$**	**1,188**

Table 15 shows the financial viability of the plant in study, this includes the economic parameters like Net Present Value equal to USD 8,276 or RWF 7,448,400 of the profit within the plant's life span of 20 years, with a simple Payback period of 2 years, that is the requred time to cover the initial investment for the plant.

Table 15.Financial viability parameters of biogas plant



Financial viability

Pre-tax IRR - equity	%	79.4%
Pre-tax MIRR - equity	%	16.9%
Pre-tax IRR - assets	%	38.1%
Pre-tax MIRR - assets	%	12.2%
Simple payback	yr	2
Equity payback	yr	1.5
Net Present Value (NPV)	$	8,276
Annual life cycle savings	$/yr	972
Benefit-Cost (B-C) ratio		3.7
Debt service coverage		2.1
GHG reduction cost	$/tCO₂	No reduction

The figure 24 bellow,was generated through RETSCreen. It gives the annual cash flow and cumulative cash flow of the plant for 20 years.

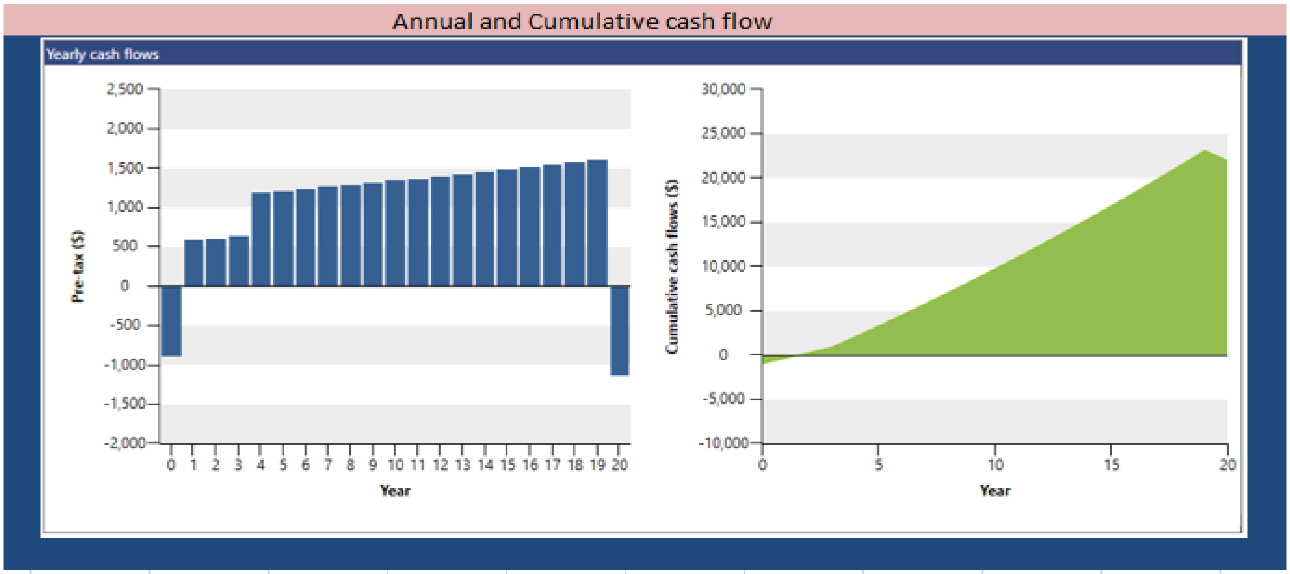


Figure 24. Annual cash and Cumulative cash flow of the plant

4.5.3. Households Incomes Level of the respondents

The results on the level of income to the families that participated in this survey indicated that, 30% earned less than 20,000 RWF, 36.4% earned between RWF 21, 000 (USD23.3) and RWF 60,000 (USD66.6), 25.5% earned between RWF 61,000 (USD 67.7) and RWF 80,000 (USD88.8) while 8.2% earned between RWF81,000 (USD 90) and RWF100,000 (USD111). This survey on the income level was simply to ensure that with the financial ability of beneficiaries with additional 50% of governmental subsidies as done for NDBP will be manageable for the upfront cost of the bio-digester plant in the study. For further figure 25 was presented.

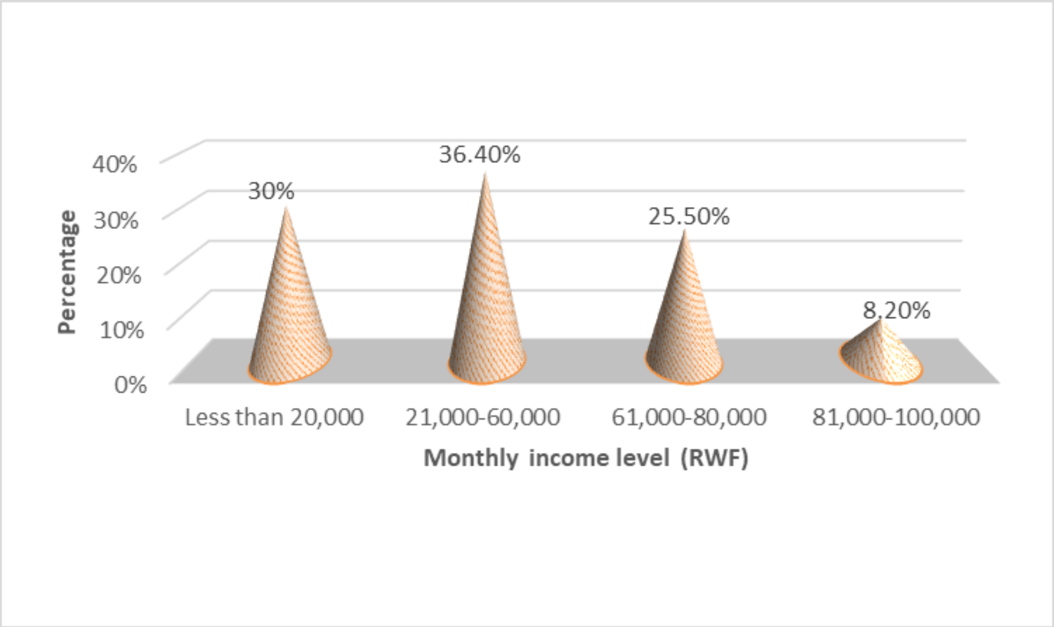


Figure 25. Households monthly Income Level

As shown on the figure 26 above, 70% of the respondent earn between RWF 252,000 (USD280) to RWF1,200,000 (USD1,333) per year. Considering the financial analysis to this project, at least each household would pay RWF 160,000 (USD177.8) as the initial payment to initiate this bio-digester plant and the after plant annual loan payment of RWF 96,480 (USD107.2) in the period of 3 years. Based on the findings of this survey, this project seems to be financially applicable for more than 60% of the households in Gicumbi district.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Energy is a backbone for economic development globally Rwanda inclusive. It plays a variety of roles ranging from industries to the households use and lack of access to the reliable energy is a constraint for sustainable development and poverty reduction. The main objective of this study was to design and evaluate the Techno-economic feasibility of a centralized co – digestion bio-digester plant for households that can use human faeces and caw dung to generate biogas that is used for cooking and heating water in the rural households of Rwanda, with case study of Gicumbi District.

Specifically, this thesis study was intended at designing this co- digestion bio-digester plant which is able to provide a reliable energy from biogas. From this point of view, the energy required for usage at household was quantified in terms of charcoal consumption per total residence. The findings of this study revealed that a bio- digester plant would help the residence to be self-reliant in terms of energy. For cooking and heating water the plant capacity was 30.82 m^3, with 25.6m^3 of digester volume, 5.22 m^3 volume of gas holder, providing 2.9 m^3 of biogas per day for the residence.

Another point was to use human faeces to improve the energy security in the rural households. Five (5) households were considered with an average family size of 5 persons generating 17.5 kg of faeces. This was co-digestion with caw dung to generate the energy needed in the residence. The use of human faeces has a direct financial benefit as the number of heads cattle that would be required to generate the same amount of energy from biogas will be reduced by almost a half.

For affordability point of view, an economic analysis for bio-digester plant in study was done by the mean of RET Screen, with preliminary purpose of evaluating the economic viability of the project. The important financial parameters such as Net Present value and Payback period were determined. And findings for this subject mentioned that for the project life time of 20 years for brick/concrete bio-digester, the Net Present Value will be USD 8, 267 or RWF7,440,300 of profit,

with payback period for initial investment of 2 years. And the survey from the respondent about the monthly income level in the households showed that at least 70% earn between RWF 21,000 (USD 23.3) to RWF 100,000 (USD111.1) monthly that implies RWF252,000 (USD 280) to RWF 1,200,0000

(USD 1,333) annually. While the financial analysis of the project indicated that each household might contribute RWF 160,000 (USD177.7) to initiate the project and pay after RWF 96,480 (USD 107) per year in the period of three years for the loan from bank that usually given at 30% of the project upfront cost after 50% of governmental subsidy for NDBP. From this observation the plant in study was found to be economically affordable for more than 60% of the households in study.

The findings of his study also revealed that, the use of this bio- digester plant would save 2.1 tons of charcoal per year for 5 households. It means that if at least 50% of households in Gicumbi District would shift from using charcoal to biogas system. From 397,871of habitants that account for 79,574 households, about 39,787 tons of charcoal will be saved per year and hence forest can be preserved in the sustainable way.

The overall findings of this study, revealed that co-digestion biogas technology can serve as an economic and environmental friendly way to provide alternative fuel; that is useful in the households mainly for cooking and heating water. This can significantly reduce the reliance on the firewood and charcoal as main energy sources for rural household in Rwanda. Hence contribute to the environmental protection through forest preservations, as well as the captures and use of methane emitted by the wastes disposals from households.

5.2. Recommendations

This master thesis present one of the approach to improve biogas dissemination technology particularly at domestic scale. Biogas technology is proved to be able to reduce the greenhouse gases emitted by fossil fuel use. Several barriers for biogas deployment and development were presented from different participants in the survey such as high up front cost; lack of information regarding the technology itself; lack of awareness regarding substrates other than caw dung mainly for domestic level; and lack of knowledge regarding technology in case of maintenance. Hence, this section discusses some recommendations to policy makers, as well as to further researchers, as contributions to overcome those barriers with the tangible results.

Firstly, for policy makers, there is need for human capacity building. This is a very essential point to increase the awareness on the biogas for households as an emerging technology far different from their tradition. Some arrangements of trainings and workshops on what is, why, how and when peoples can use biogas technology is very crucial.

Encourage people to understand the importance of using biogas either socially; as it reduces the indoor air pollution and save time spent for women and children for collecting firewood and residues, or economically; as it generates incomes in terms of fertilizers, and long term money saving for those who use to buy charcoal or firewood.

Policy makers can help people to be facilitated with loans from many banks as possible so that the biogas system can be built at large number throughout the country.

Secondly, more alternative co-digestion technologies are recommended as the findings of this study have shown that co-digestion can be an economic way to access on a biogas at household levels.

This study adopted charcoal to biogas energy equivalence comparison for designing the required bio-digester plant among the others. Still the research is needed for the cheapest as possible, more affordable and reliable way to supply energy for cooking in the rural households other than firewood and charcoals.

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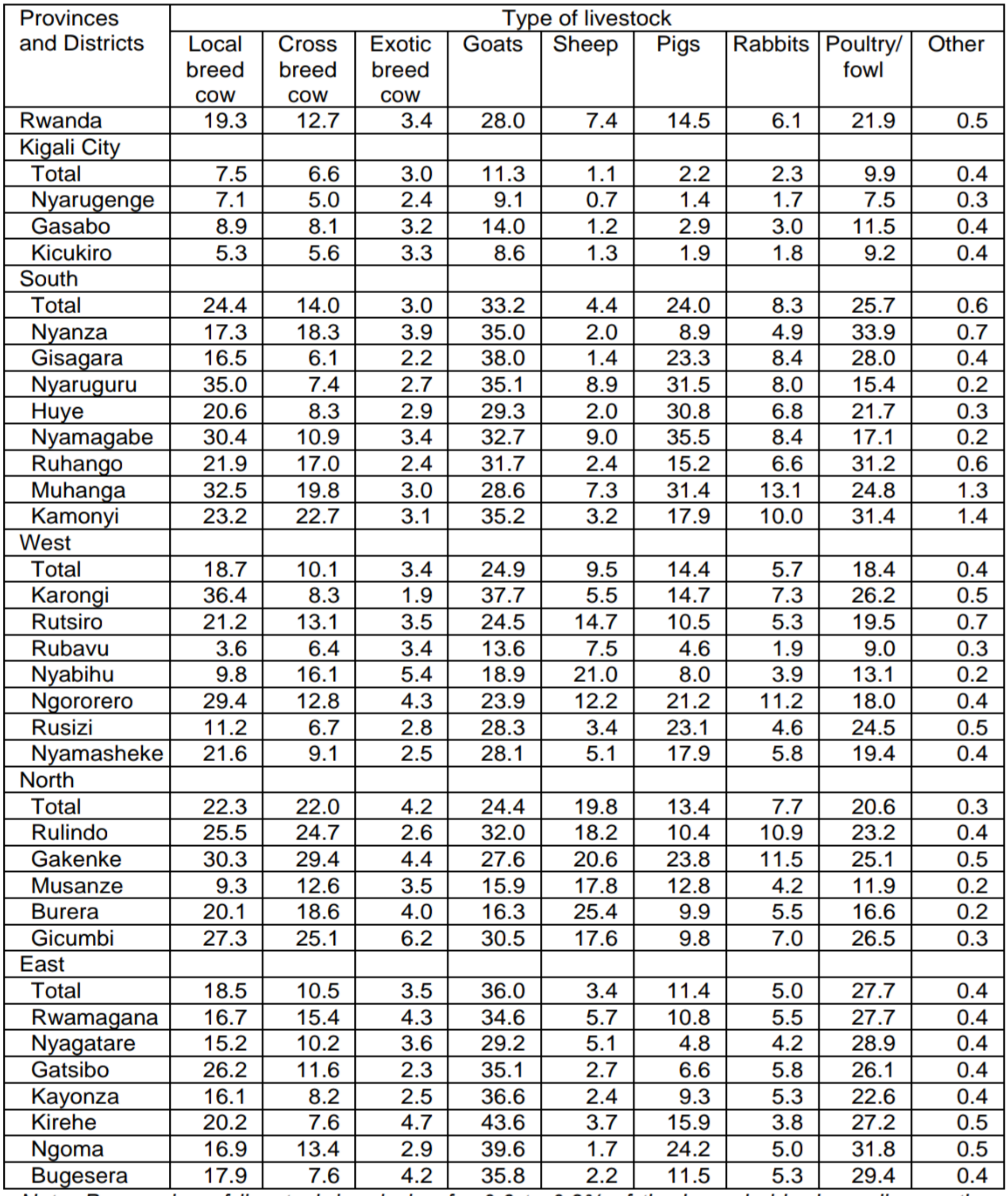
APPENDICES

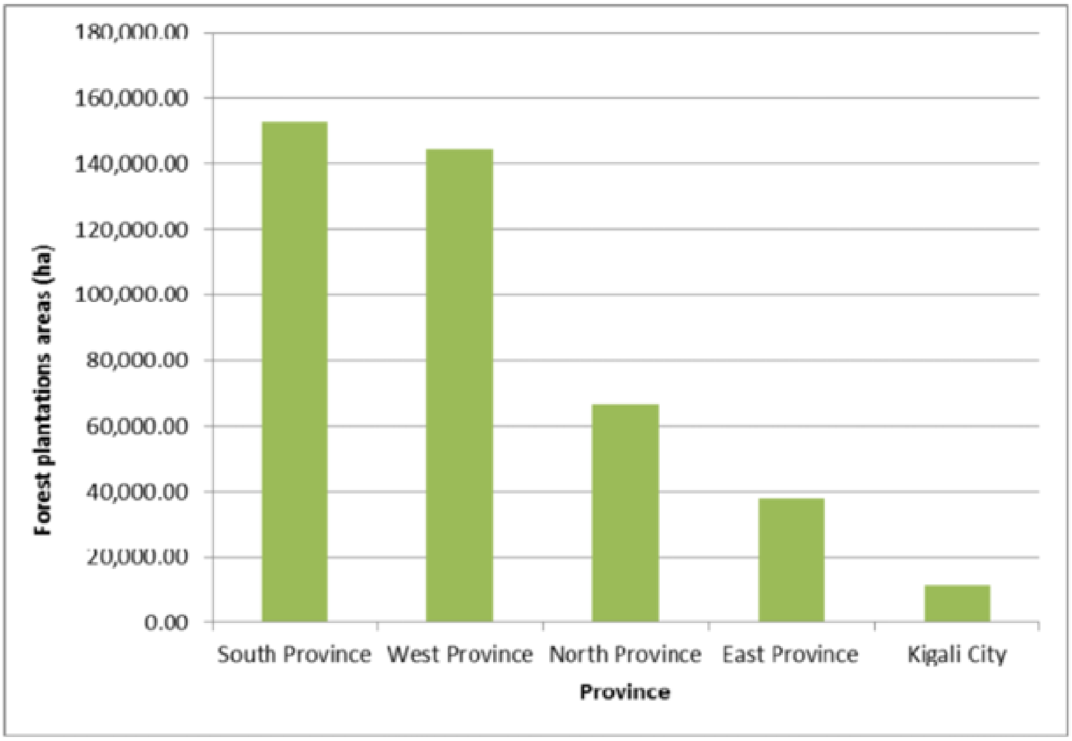
Appendix1. Percentage of households with livestock per Province and District

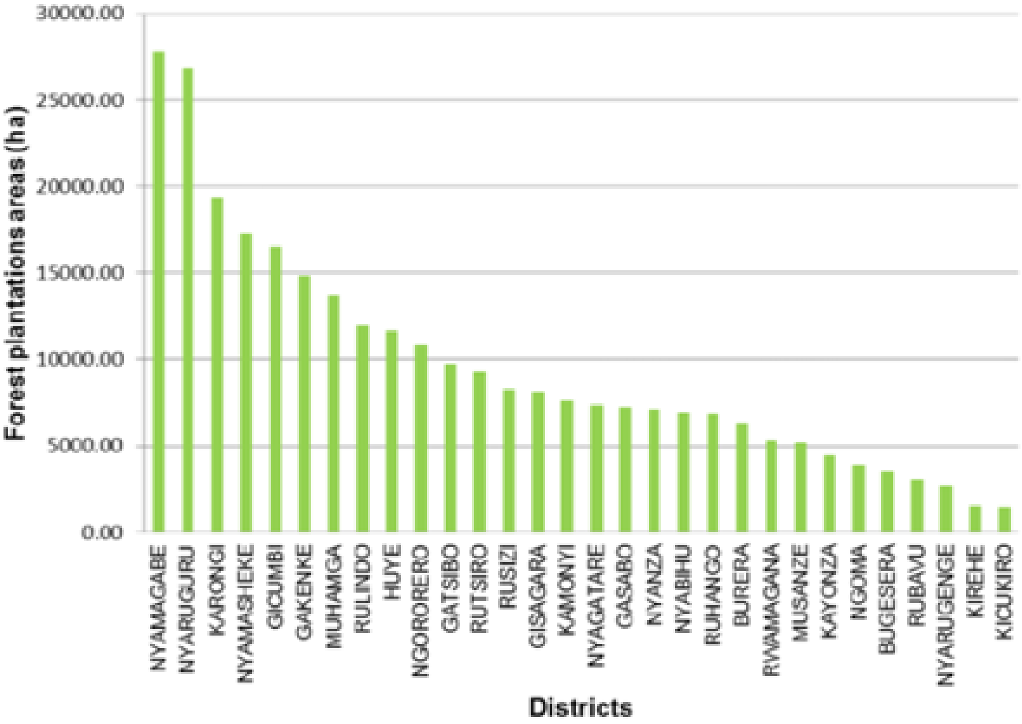


Provinces and Districts	Type of livestock								
	Local breed cow	Cross breed cow	Exotic breed cow	Goats	Sheep	Pigs	Rabbits	Poultry/ fowl	Other
Rwanda	19.3	12.7	3.4	28.0	7.4	14.5	6.1	21.9	0.5
Kigali City									
Total	7.5	6.6	3.0	11.3	1.1	2.2	2.3	9.9	0.4
Nyarugenge	7.1	5.0	2.4	9.1	0.7	1.4	1.7	7.5	0.3
Gasabo	8.9	8.1	3.2	14.0	1.2	2.9	3.0	11.5	0.4
Kicukiro	5.3	5.6	3.3	8.6	1.3	1.9	1.8	9.2	0.4
South									
Total	24.4	14.0	3.0	33.2	4.4	24.0	8.3	25.7	0.6
Nyanza	17.3	18.3	3.9	35.0	2.0	8.9	4.9	33.9	0.7
Gisagara	16.5	6.1	2.2	38.0	1.4	23.3	8.4	28.0	0.4
Nyaruguru	35.0	7.4	2.7	35.1	8.9	31.5	8.0	15.4	0.2
Huye	20.6	8.3	2.9	29.3	2.0	30.8	6.8	21.7	0.3
Nyamagabe	30.4	10.9	3.4	32.7	9.0	35.5	8.4	17.1	0.2
Ruhango	21.9	17.0	2.4	31.7	2.4	15.2	6.6	31.2	0.6
Muhanga	32.5	19.8	3.0	28.6	7.3	31.4	13.1	24.8	1.3
Kamonyi	23.2	22.7	3.1	35.2	3.2	17.9	10.0	31.4	1.4
West									
Total	18.7	10.1	3.4	24.9	9.5	14.4	5.7	18.4	0.4
Karongi	36.4	8.3	1.9	37.7	5.5	14.7	7.3	26.2	0.5
Rutsiro	21.2	13.1	3.5	24.5	14.7	10.5	5.3	19.5	0.7
Rubavu	3.6	6.4	3.4	13.6	7.5	4.6	1.9	9.0	0.3
Nyabihu	9.8	16.1	5.4	18.9	21.0	8.0	3.9	13.1	0.2
Ngororero	29.4	12.8	4.3	23.9	12.2	21.2	11.2	18.0	0.4
Rusizi	11.2	6.7	2.8	28.3	3.4	23.1	4.6	24.5	0.5
Nyamasheke	21.6	9.1	2.5	28.1	5.1	17.9	5.8	19.4	0.4
North									
Total	22.3	22.0	4.2	24.4	19.8	13.4	7.7	20.6	0.3
Rulindo	25.5	24.7	2.6	32.0	18.2	10.4	10.9	23.2	0.4
Gakenke	30.3	29.4	4.4	27.6	20.6	23.8	11.5	25.1	0.5
Musanze	9.3	12.6	3.5	15.9	17.8	12.8	4.2	11.9	0.2
Burera	20.1	18.6	4.0	16.3	25.4	9.9	5.5	16.6	0.2
Gicumbi	27.3	25.1	6.2	30.5	17.6	9.8	7.0	26.5	0.3
East									
Total	18.5	10.5	3.5	36.0	3.4	11.4	5.0	27.7	0.4
Rwamagana	16.7	15.4	4.3	34.6	5.7	10.8	5.5	27.7	0.4
Nyagatare	15.2	10.2	3.6	29.2	5.1	4.8	4.2	28.9	0.4
Gatsibo	26.2	11.6	2.3	35.1	2.7	6.6	5.8	26.1	0.4
Kayonza	16.1	8.2	2.5	36.6	2.4	9.3	5.3	22.6	0.4
Kirehe	20.2	7.6	4.7	43.6	3.7	15.9	3.8	27.2	0.5
Ngoma	16.9	13.4	2.9	39.6	1.7	24.2	5.0	31.8	0.5
Bugesera	17.9	7.6	4.2	35.8	2.2	11.5	5.3	29.4	0.4

Source: (NISR, 2012)

Appendix 2. Distribution of the forest Plantations areas per Province and District





Source: (Nduwamungu. J., et al,2013)

Appendix 3. Questionnaires

Dear Respondent,

The researcher is a student in Masters of Science in Energy Engineering track at the Pan African University Institute of Water and Sciences. (*Including climate change*), PAUWES in Tlemcen, Algeria. You have been selected to be part of this study as one of the best respondent due to your unique experience about operations of biogas plants or as you are intended as pilot study for provision of centralized co-digester systems. Kindly spare some few minutes of your busy schedule and respond to these questions by giving vital views where needed and ticking one of the alternatives given. The information obtained will be used for academic purposes and we ensure you to treat the information with utmost confidentiality.

SECTION A: BACKGROUND DATA

A. Household head		
1.	Father	☐
2.	Mother	☐
3.	Other (Specify)	☐
B. Indicate the family size		
1.	Less than 3	☐
2.	3-5 members	☐
3.	6-12 members	☐
4.	More than 12	☐
C. Income level per month (RWF)		

1	Less than 2000	☐
2	2,1000 -60,000	☐
3	61,000- 80,000	☐
4	81,000- 100,000	☐
5	More than 100,000	☐
D. How long have you owned a biogas system? (if applicable)		
1	Less than 6 months	☐
2	6-12 months	☐
3	12-18 months	☐
4	More than 18 months	☐

SECTION B: HOUSEHOLDS ENERGY SYSTEMS

This section measures the performance of your energy systems in term of provision of energy and serving the intended purpose. Kindly respond to the following statements as honest as possible.

A. Fuel types for cooking and heating water		
1	Firewood	☐
2	Charcoal	☐
3	Dung cake	☐
4	LPG	☐
5	Electricity	☐

6	Biogas	☐
7	Other (specify)	☐
B. Monthly fuel consumption (Quantities), where applicable		
1	Firewood	☐
2	Charcoal	☐
3	Dung cake	☐
4	LPG	☐
5	Electricity	☐
6	Biogas	☐

C. How long have you been using charcoal (as selected reference fuel)		
1	Less than 6 months	☐
2	6-12 months	☐
3	12-18 months	☐
4	More than 18 months	☐
D. Monthly expenditure for cooking fuel (RWF)		
1	Firewood	☐

2	Charcoal	☐
3	Dung cake	☐
4	LPG	☐
5	Electricity	☐
6	Biogas	☐
7	Other (Specify)	

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E. How much money do you spend on maintenance of your biogas systems (Rwf)? if applicable

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……………………………………………………………………………………………………

G. Does your biogas system meet all your energy demands? If applicable

a) Yes ☐

b) No ☐

H. Explain your answer in G above

……………………………………………………………………………………………………

……………………………………………………………………………………………………

SECTION C: Open discussion schedule with Technicians/ Supervisors/Supplies

This section intends to seek the opinions of service providers or supervisors in charge of NDBP deployment, price overview on the construction items and the social impacts of biogas technology.

1. Do you think it is necessary to encourage biogas technology deployment in households?

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2. Do you think there is a difference in lifestyle (Economically or Socially) for households having biogas digesters in their homes and those without biogas?

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3. Explain what do you think to be the barrier for diffusion of biogas technology in Households?

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4. What is the perception of customers towards NDBP deployment?

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5. How often do you arrange households' trainings and workshops on the use of biogas plants?

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6. What are the approaches do you use for dissemination of biogas system program mainly NDBP?

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Appendix 4: Research grant Budget allocation

Nº	**Item Description**	**Total amount(USD)**
1	Flight ticket	1000
2	Data collection expenses(field visits, research assistant payment)	1280
3	Questionnaires printing and photocopies	250
4	Internet recharge in Total	250
3	Software assistance, and (Licensing) from REPC ltd company	100
4	Final thesis and internship report printing and Binding	90
5	International money transfer fees	30
Total		3,000