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# SOLAR-AIDED ANAEROBIC DIGESTER SYSTEM FOR SMALL SCALE APPLICATION IN UGANDA

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**Date: 28th / August / 2016**

*Master in **Energy Engineering track***

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# SOLAR-AIDED ANAEROBIC DIGESTER SYSTEM FOR SMALL SCALE APPLICATION IN UGANDA

A Thesis Report Submitted in Partial Fulfillment of the Requirements of the award of a Master in Energy (Engineering Track) at Pan African University Institute of Water and Energy Sciences (Including Climate Change)

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# DECLARATION

I, **Nicholas Mukisa** declare that the entirety of this thesis work contained therein is my own, original work, that I am the sole author thereof, save for the extent explicitly otherwise stated. Each contribution to this thesis work from the work(s) of other people has been explicitly attributed, and has been cited and referenced.

**Signature:** **Date:** 28th / August / 2016

# DEDICATION

To whoever has interest in biogas production, more so to the Pan Africans who believe in saving the beautiful environment through reservation and protection of the existing natural biomass and venturing into the utilization of the piling organic waste in the cities and farms for energy production.

To every African child to whose ear it has been whispered, "*You will never make it nor mount to anything in life."* Stand firm and do your better, not even the sky is the limit! You will become who you ought to be in life.

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# ABSTRACT

Access to reliable and affordable energy is a sustainable development goal whose achievement calls for every stakeholder's input. The drive to combat energy poverty in rural communities especially in African countries relies on the utilization of the available energy resources, mainly the renewables.

At 6.9 % electrification of rural households, majority of Ugandans cannot use electricity nor liquefied natural gas to cook. 70 % of total energy requirements of households are met by use of paraffin and firewood with over 53 % of lighting needs being met by use of paraffin.

As result high firewood demand, Uganda's total forest cover has reduced by 46.9 % over a period of 20 years since 1990. The country is anticipated to import firewood in the year 2020 if the current rates of deforestation and fuelwood consumption are not regulated. This calls for an urgent attention to the exploitation of the existing renewable energy resources like solar and bioenergy to improve energy access in the country and to mitigate climate change.

A small scale solar-aided anaerobic digester system for household application was designed and simulated in this study to assess the possibility of using solar heating in the tropical regions, specifically in Uganda to supply the heat energy requirements of an anaerobic digester using cattle manure as its feedstock operating in thermophilic temperatures. The produced biogas was intended to replace 75 % of firewood use for cooking to minimize greenhouse gas emissions and the health hazards related to its use.

In this study, Kiruhura district was used as the case study site considering the abundance of cattle, thus cattle manure production in the area with an average of 7 cattle per household producing 14 kg each of dung per day. A household was considered to constitute of 7 persons and utilizing 1.56 $m^3$ of firewood to meet their cooking energy demands per year.

The designed system comprises of a 2.00 $m^3$ anaerobic digester heated by hot water flowing from a 1.00 $m^3$ storage tank through a copper tube of 31.17 m coiled around its inner wall. The hot water tank is heated by a solar collector heating system constituting of 5 glazed flat plate solar collectors operating on thermo-siphoning principle.

The designed anaerobic digester system was found to operate in temperatures ranging from 50 ℃ to 60 ℃ and only falling to 47 ℃ when the site receives the worst irradiance-incident during May 28$^{th}$ to June 1$^{st}$ and November 14$^{th}$ to 18$^{th}$. The solar heating system delivers hot water in the temperature range of 50 ℃ to 67 ℃ throughout the year and only less than 50 ℃ during the worst irradiance-incident. The hot water tank temperatures vary between 50 ℃ and 60 ℃ but also falling to about 40 ℃ during the worst irradiance-incident of the site. The anaerobic digester temperature on average takes 6 and 10 hours, respectively, for best and worst irradiance-incident periods to vary by 1 ℃ at a design hot water flow rate of 44 kg/h to the digester heating system. The digester operates in the thermophilic temperature range, that is 47 ℃ to 60 ℃ throughout the year.

The digester was sized for a daily influent of 0.06 $m^3$ and hydraulic retention time of 27 days, producing on average 2.22 $m^3$ of biogas per day at an operating temperature of 50 ℃. Incorporation of heating system to the digester to heat it from 21 ℃, for ambient operating digester to 50 ℃, for thermophilic operating digester was found to result in biogas production increment of 1.29 $m^3$ per day.

The levelized cost of energy (LCOE) for the designed system of productive period of 30 years was found as 227.78 UgShs/kWh and 0.589 cost-benefit ratio for a system implemented at 50 % loan share of the investment cost with a Feed-in Tariff of 386.92 UgShs/kWh. A sensitivity analysis of LCOE to $\pm$ 10 % change in the system parameters was carried out; LCOE showed 8.98 % decrease for 10 % increase in daily cattle manure used and 10.93 % increase for 10 % decrease in daily cattle manure used. There was a direct reflection of $\pm$ 10 % in the LCOE for $\pm$ 10 % change in the investment costs of the system. The hydraulic retention time yielded 2.73 % decrease in LCOE when increased by 10 % and 2.98 % increase in LCOE when decreased by 10 %.

With biogas replacing 75 % of all firewood usage for the cooking activities, the household would avoid GHG emissions of 4, 403.94 $kg_{CO_{2eq.}}$ per year, 99.9 % of emissions if firewood had been used for cooking and cattle manure left unattended to in open space other than being used in the anaerobic digester. With the designed system in this study, 132.12 $T_{CO_{2eq.}}$ GHG emissions would be avoided in a period of 30 years and saving environment by not encroaching on the forests and woodlands in search for firewood.

# PREFACE

L'accès à une énergie fiable et abordable est un objectif pour le développement durable dont la réalisation demande la contribution de toutes les parties prenantes. La volonté de lutter contre la pauvreté énergétique dans les communautés rurales, en particulier dans les pays africains repose sur l'utilisation des ressources énergétiques disponibles, principalement les énergies renouvelables.

Pour un taux d'électrification des habitations rurales de 6,9 %, la majorité des Ougandais ne peuvent pas utiliser l'électricité, ni le gaz naturel pour la cuisson. Un pourcentage de 70 % des besoins énergétiques totaux de ces habitations sont satisfaits par l'utilisation de paraffine et de bois de chauffage avec plus de 53 % des besoins d'éclairage étant satisfaite par l'utilisation de la paraffine.

A cause de l'augmentation de demande en bois de chauffage, la couverture forestière totale de l'Ouganda a chuté de 46,9 % sur une période de 20 ans depuis 1990. Le pays a donc anticipé d'importer du bois de chauffage vers l'an 2020 si les taux actuels de déforestation et de la consommation de bois de feu ne sont pas réglementés. Cela exige une attention urgente à l'exploitation des ressources énergétiques renouvelables existantes comme l'énergie solaire et la bioénergie pour améliorer l'accès à l'énergie dans le pays et à réduire l'effet de changements climatiques.

Un système de digestion anaérobique solaire assistée à petite échelle pour l'application à des habitations a été conçu et simulé dans cette étude afin d'évaluer la possibilité d'utiliser le chauffage solaire dans les régions tropicales, en particulier en Ouganda pour fournir les besoins en énergie de la chaleur demander d'un digesteur anaérobique en utilisant le fumier de bétail comme la charge d'alimentation fonctionnant à des températures thermophiles. Le biogaz produit était destiné à remplacer 75 % de l'utilisation du bois de chauffage pour la cuisson pour réduire les émissions de gaz à effet de serre et les risques sanitaires liés à son utilisation.

Dans cette étude, la ville de kiruhura a été prise comme un cas d'étude a cause de l'abondance du bétail, ainsi la production de fumier de bétail dans la région avec une moyenne de 7 bétail par maison, avec une production de 14 kg de fumier par jour pour chaque betail. Une habitation a été considéré comme constituant de 7 personnes et en utilisant 1,56 $m^3$ de bois de chauffage pour répondre à leurs besoins en énergie de cuisson par an.

Le système conçu est composé d'un digesteur anaérobique de 2,00 $m^3$ chauffé par l'eau chaude circulant à partir d'un réservoir de 1,00 $m^3$ de stockage à travers un tube de cuivre de 31,17 m enroulé autour de sa paroi intérieure. Le réservoir d'eau chaude est chauffé par un système de chauffage de capteur solaire constitutif de 5 capteurs plans vitrés solaires fonctionnant avec le principe de thermo-siphon.

Le système de digestion anaérobique conçu a été utiliser pour fonctionner dans des températures allant de 50 °C à 60 °C et ne tombant à 47 °C que lorsque le site reçoit la plus mauvaise irradiation solaire au cours 28eme Mai au 1er Juin et le 14 Novembre au 18eme. Le système de chauffage solaire fournit de l'eau chaude dans l'intervalle de température de 50 °C à 67 °C pendant toute l'année et seulement moins de 50 °C pendant les pires cas d'irradiation. Les températures de réservoir d'eau chaude varient entre 50 °C et 60 °C, mais aussi tombait à environ 40 °C pendant les pires cas d'irradiation sur site. La température du digesteur anaérobique prend en moyenne 6 et 10 heures, respectivement, pour les meilleures et les mauvaises périodes d'irradiante-incidents pour faire varier de 1 °C à une conception de débit d'eau chaude de 44 kg/h pour le système de chauffage du digesteur. Le digesteur fonctionne dans la l'intervalle de température thermophile, soit 47 °C à 60 °C pendant toute l'année.

Le digesteur a été dimensionné pour une affluente journalière de 0,06 $m^3$ et un temps de rétention hydraulique de 27 jours, produisant du biogaz avec une moyenne de 2,22 $m^3$ par jour à une température de fonctionnement de 50 °C. L'incorporation du système de chauffage à l'autoclave pour chauffer de 21 °C, à température ambiante de fonctionnement digesteur à 50 °C pour le digesteur thermophile d'exploitation a été constaté que la production de biogaz entraîner une augmentation de 1,29 $m^3$ par jour.

Le coût unitaire moyen de l'énergie produite (LCOE) par le système conçu pour la période de production de 30 ans a été trouvé de 227,78 ShsUg/kWh et 0,589 de rapport coût-bénéfice pour un système mis en place à 50 % de parts de prêt du coût d'investissement avec un tarif de rachat de 386,92 ShsUg/kWh. Une analyse de coûts du LCOE à ± 10 % de variation dans les paramètres

du système a été effectuée ; LCOE a montré 8,98 % de baisse pour 10 % d'augmentation journalier de fumier de bétail utilisé et 10,93 % d'augmentation pour une baisse de 10 % par jour fumier de bétail utilisé. Il y avait un reflet direct de ± 10 % dans le LCOE pour ± 10 % variation dans les coûts d'investissement du système. Le temps de rétention hydraulique a abouti à la diminution de 2,73 % en LCOE lorsqu'il augmente de 10 % et 2,98 % d'augmentation en LCOE quand il diminuer de 10 %.

Lors d'un remplacement de 75 % de l'utilisation du bois de chauffage pour les activités de cuisson par le biogaz, les habitants vont permettre d'éviter les émissions des gaz à effet de serre (GES) de 4. 403,94 $kg_{CO_{2eq.}}$ par an, 99,9 % des émissions si le bois de chauffage avait été utilisé pour la cuisson et le fumier de bétail reste sans surveillance dans un espace ouvert autre que d'être utilisé dans le digesteur anaérobique. Avec le système conçu dans cette étude, 132,12 $T_{CO_{2eq.}}$ les émissions de GES serait évitée pour une période de 30 ans tout en protégeant l'environnement de la déforestation en cherchant du bois pour le chauffage.

**Keywords:** Anaerobic digestion, Solar energy, Cattle manure, Thermophilic temperature, Kiruhura district

**Mots clé:** Digestion anaérobique, Energie solaire, Fumier de betail, Temperature thermophilique, Quartier Kiruhura

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## NOMENCLATURE

| | |
|---|---|
| AD | Anaerobic Digester |
| BMBF | German Ministry of Higher Education and Research |
| BOD | Biochemical Oxygen Demand |
| BoU | Bank of Uganda |
| CH4 | Methane |
| CO2 | Carbon dioxide |
| COD | Chemical Oxygen Demand |
| COP | Conference of parties |
| CPC | Compound Parabola Concentrator |
| CSTR | Continuous Stirred- Tank Reactors |
| EES | Engineering Equation Solver software |
| EF | Emission Factor |
| EPA | Environmental Protection Agency |
| FiT | Feed in-Tariff |
| FRP | Fibreglass-Reinforced Polyester |
| GHG | Greenhouse Gas |
| GTZ | German Technical Cooperation |
| H2 | Hydrogen |
| HRT | Hydraulic Retention Time |
| IRENA | International Renewable Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| LCOE | Levelized Cost of Energy |
| OLR | Organic Loading Rate |
| PFR | Plug Flow Reactors |
| PPDA | Public Procurement and Disposal Asset Authority |
| PVC | Polyvinyl Chloride |
| SBR | Sequencing Batch reactors |
| SDG | Sustainable Development Goals |
| SRT | Solid Retention Time |
| TFR | Tubular Flow Reactors |
| TS | Total Solids |
| UASB | Up flow Anaerobic Sludge Blanket reactors |
| UBOS | Uganda Bureau of Statistics |
| Ug Shs | Uganda Shilling |
| USD | United States Dollar |
| VFA | Volatile Fatty Acids |
| VS | Volatile Solids |
| WGV | Wertstoffgewinnungs- und Vermarktungsgesellschaft |
| $A$ | Area |

| | |
|---|---|
| $C_p$ | Heat capacity at constant pressure |
| $\dot{Q}$ | Rate of Energy change |
| $\dot{m}$ | Mass flow rate |
| $D, d$ | Diameter |
| $G$ | Global incident solar radiation on the collector |
| $h$ | Height |
| $K$ | First-order rate constant |
| $L$ | Length |
| $M, m$ | Mass |
| $Nu$ | Nusselt number |
| $P$ | Pressure |
| $Pr$ | Prandtl number |
| $Q$ | Energy |
| $R$ | Gas constant, Coefficient of correlation |
| $Ra$ | Rayleigh number |
| $Re$ | Reynolds number |
| $T$ | Temperature |
| $U$ | Overall heat transfer coefficient |
| $V$ | Volume |
| $Y$ | Cumulative methane yield |
| $k$ | Heat conductivity |
| $t$ | Time |
| $v$ | Kinetic viscosity |
| $\gamma$ | Methane production rate |
| $\eta$ | Efficiency |
| $\mu$ | Dynamic viscosity |
| $\rho$ | Density |

# Chapter 1. INTRODUCTION

**Outline:**

## 1.0 Introduction

This chapter gives a brief background of the study work, motivation, objectives, justification and inclusions and exclusions of the research that was carried out.

## 1.1 Background

Humanity is currently faced with the life threatening challenge of climate change especially as a result of many years of greenhouse gases (GHG) emissions from the utilization of fossil fuels. From the conference of parties twenty-first session held in Paris (COP21), parties have to honor their global annual greenhouse gases mitigation pledges by 2020 and take appropriate pathway to hold global average temperature increase below 2 °C above preindustrial levels and limiting temperature increase to 1.5 °C [1]. A massive increase in the deployment and employment of renewable energies is a key mitigation strategy to keep global warmth at less than 2 °C.

The use of biomass as a viable replacement for fossil fuels has been a fundamental area of research; biogas production takes central focus because of its potential to capture the powerful GHG methane, (with a global warming potential of 25 times that of carbon dioxide) [2], that is emitted from decomposition of organic matter in landfills and traditional manure management systems that is of negative impact to climate.

Biogas is a combustible mixture of gases, mainly methane and carbon dioxide, produced through microbial degradation of various types of organic matter where complex organic molecules such as carbohydrate, proteins and fats are transformed through a multistep microbial-mediated biochemical pathway [3]. The gases are waste products of the respiration of decomposer microorganisms with their composition dependent upon the decomposing substance [4].

The phenomenon of naturally produced biogas has been known since the 17th century and in mid-19th century, experimental construction of actual biogas systems and plants commenced with the septic tank as the oldest biogas system. However, the development in biogas systems nearly stopped by the end of the 1950s due to the low cost of the fossil fuels; oil and gas, only to be reawakened in mid-1970 following the oil crisis in 1973 [4].

For the global carbon cycle balance, microbial-controlled production of biogas is an important part with an estimate of 590–800 million tons of methane being emitted into the atmosphere every year from natural biodegradation of organic matter under anaerobic conditions [5]. Utilization of biogas digester systems to generate biogas from various decomposing types of biomass provides an energy source for vast purposes that is crucial in the global move towards green energy [5].

Anaerobic digestion process for biogas production is a temperature sensitive process where average operating temperature affects the process reaction rate and its fluctuations affect the reaction stability [6]. It is noted that the hourly temperature fluctuations should be maintained in the range of 2 – 3 ℃ since fluctuations exceeding 5 ℃ in a short period result in significant decrease in biogas yield [7]. The anaerobic digestion process is categories into three temperature diapasons for microbial activity, that is, psychrophilic (temperature diapason < 25 $^0$C), mesophilic (25 – 40 $^0$C) and thermophilic (> 40 $^0$C) regimes of bioconversion [8]. Thermophilic temperature diapason yields the highest biogas production of all the diapasons. In order to enhance the effectiveness of an anaerobic digestion process, external heating sources such as fossil fuels, solar heating or diversion of part of the produced biogas can be used to increase the digester temperature steadily [8] [9].

The use of solar heating systems to heat the anaerobic digester can be tracked back to the 1980s, where a compound parabola concentrator (CPC) digester was warmed using solar energy [10]. In recent years, use of solar energy as an alternative heating source has been studied and implemented [9]. Solar heating systems have been incorporated in the anaerobic digester to optimize and stabilize the temperature in the digester for effective microbial activity and biogas production. It has been noted that solar energy incorporation accelerates biogas production in the period of time [11].

With the incorporation of solar heating system in the anaerobic digester, the digester efficiency has been improved with higher biogas yield noted for the different biomass feed stocks used. However, there is still room for further study on the incorporation of solar heating for digesters operating in thermophilic temperature range for small scale application in tropical regions.

## 1.2 Motivation

Energy poverty still remains a big challenge for the Republic of Uganda regardless of all the renewable energy resources it is endowed with. The exploitation of these renewable energies and extension of the grid line to rural areas of the country are still pending ventures in the country.

As the extension of the grid line remains at a standstill, communities have to opt for other sources of energy to meet their energy needs. Since the country's economy majorly relies on agriculture, biogas production from the agricultural waste is a merging potential means of meeting the households' energy needs other than relying on fossil fuels. The feedstock is readily and freely available to every household in form of farm waste from crop harvests and animal manure.

Uganda is located in the tropics, thus experiencing equatorial climate with solar radiation throughout the year. Such climate fosters the operation of anaerobic digesters at relatively constant temperatures throughout the year. However, for optimal digester yield, an external heating system is required to elevate the digester temperature to the mesophilic or thermophilic conditions which are characterised with higher biogas production. Heating sources like solar heating, fossil fuel heating or even diverting part of the produced biogas to heat the digester have been widely used especially for places experience winter seasons.

In this thesis, a small scale solar-aided anaerobic digester system was designed for application in Uganda, taking Kiruhura district as the case study to operate in the thermophilic range using the available livestock waste as feedstock. Though solid-aided anaerobic digester have been tried out in low temperature areas, especially with winter conditions, this study puts its emphasis on utilizing the concept in tropics.

## 1.3 Objectives

The main objective of this research was to design, simulate and evaluate a solar-aided anaerobic digester system operating in thermophilic conditions for small scale application in Kiruhura district, Uganda.

The main objective was further subdivided into the following objectives:

i. To validate the anaerobic digester model of the study

ii. To design and optimize the operation of the anaerobic digester system.

iii. To design and optimize a solar collector and heating system.

iv. To simulate the solar-aided anaerobic digester system designed in the study.

v. To evaluate the feasibility of solar-aided anaerobic digester system in Kiruhura district.

vi. To evaluate the environmental impact of the system.

## 1.4 Justification

This research was worthy undertaking because the findings of solar-aided anaerobic digester are of importance in that;

i. They render a basis for further research in the area of biogas plant designing and restructuring of the digester for domestic application.

ii. They are a mitigation mechanism to health hazards caused by use of wood and paraffin.

iii. They are a mitigation mechanism to climate change.

## 1.5 Inclusions and Exclusions

The study includes a brief background of the case study that this thesis is based on, literature on using solar heating to heat anaerobic digestion. In the study different anaerobic digester plant configurations were discussed. The environmental and process factors that affect anaerobic digestion were limited to only the main factors. Temperature effect on the anaerobic digester was emphasized in this study.

The feedstock of the anaerobic digester for the case study was considered at thickening of 8 % solids, and the actual thickening evaluation process is included in the study literature. Further treatment of the effluent and supernatant drained from the anaerobic digester plant by secondary and tertiary treatment processes to fertilizer and portable water was excluded from this study.

The study includes the energy production of the different anaerobic digester plant concepts, but the biogas production rates for the different concepts were calculated only including one variable of the digestion process. The study excludes modelling of converting the biogas generated by the anaerobic digester plant concepts to electricity.

To determine the heat and energy requirements of the different anaerobic digester plant concepts, the study includes numerical heat and energy balance concepts taking the following aspects into account: incoming feedstock heat demand, available heat, incoming solar irradiation on collectors, convection, conduction and radiation losses to the surrounding from digester as well as heat losses due to mass transfer. Validation of the anaerobic digester system model was included in this study.

This study includes the feasibility study of the system. Cost of feedstock transportation to the plant was excluded in this study. Land requirement and water for the system were considered to be available to individual households.

# Chapter 2. LITERATURE REVIEW

**Outline:**

## 2.0 Introduction

This chapter provides a general overview of some of the main aspects of this study, that is, research case study, anaerobic digestion (AD) system, solar heating system, heat energy conversion system and review of their previous mathematical simulations. The purpose is to give some background information to the methodology and interpretation of the results presented in the subsequent chapters.

## 2.1 Research Case Study

Rural electrification is still a big challenge the government of Uganda is faced with. The Uganda Bureau of Statistics (UBOS) reported that only 6.9 % of rural households access the grid electricity, which is also characterized with continuous daily load shedding. At National level, 70 % of total energy requirements of households are met by paraffin and firewood usage, with over 53 % of lighting needs being met by use of paraffin. There is an urgent need for immediate attention and action to mitigate climate change due to the escalading deforestation in search for firewood and the related health hazards that come as a result of persistent use paraffin and firewood [12]. Uganda's energy consumption stands at 1 % electricity, 10 % petroleum products and 89 % biomass which comprises of 4.7 % residues, 5.6 % charcoal and 78.6 % firewood [13].

In 1990, total forest cover was 20.4 % of the land area of the country and by 2010, Uganda had lost 2.3 million hectares of 4.9 million hectares of total forest cover in 1990, mounting to a reduction of 46.9 % over a period of 20 years. Thus, the total forest cover stood at 11 % of the land area of Uganda in 2010 [14]. The Ministry of Water and Environment (MWE) anticipates that Uganda could import firewood in the year 2020 if the current rates of deforestation and fuelwood consumption are not regulated [15].

Notable for solar potential, Uganda receives insolation of averagely 4-5 $\mathrm{kWh/m^2/day}$ for the entire year for all the regions of the country [16], with an average of 6 sunshine hours per day and an average ambient temperature of $25℃$ [17]. However, only 10.6 % of households at the National level use solar energy [12].

Although agriculture is the backbone of Uganda's economy, accounting for 42 % of GDP [18], biogas production and usage from numerous available agricultural wastes is not evaluated among the sources harvested in the country because of its negligible contribution [12].

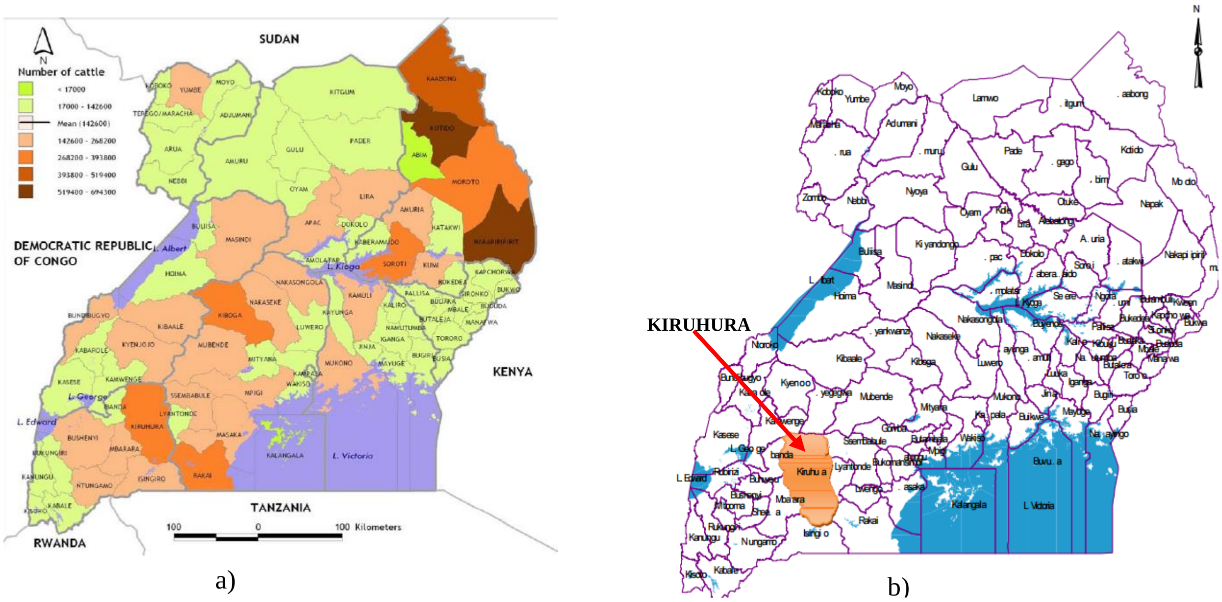
In Uganda, about 4.5 million households (70.8 %) have livestock or poultry, and only 2.4 % of the households have additional planted pasture, which reflects the fertility of the soil, thus the reliance on natural pasture for livestock rearing. In 2008, about 26.1 % of all households in the country owned cattle with a typical cattle-owning household on average owning seven (7) cattle [19]. Figure 2. 1 below shows some of the local breeds of cattle reared in Uganda [19].

*Source: UBOS, 2008*

**Figure 2. 1: Some of the local cattle breeds reared in Uganda**

### 2.1.1 Case study site

Kiruhura district in Western Uganda, located on coordinates: latitude 0.1928 ° S and longitude 30.8039 ° E, altitude of 1, 372 metres above sea level and total area of 4, 608 $km^2$ was considered as the case study site for this research. It neighbors with Mbarara, Isingiro, Lyantonde, Rakai, Ssembabule, Kamwenge and Ibanda districts. The district has a savannah woodland type of vegetation and also endowed with water bodies such as Lake Mburo and Lake Kacheera. It is one of the leading cattle rearing districts in the country. Figure 2. 2 below shows the cattle rearing districts of Uganda [19].




*Source: UBOS, 2008*

**Figure 2. 2: Map of Uganda showing: a) Total number of cattle by district; and b) Geographical location of Kiruhura district**

With all the proven renewable energy resources Kiruhura district has, its settlers have no access to affordable and reliable electricity to rely on for their domestic cooking demands. They mainly rely on traditional biomass and paraffin for their household energy needs. In this study, a small scale energy generating system utilizing the available renewable resources, namely, solar resource, biomass resource, specifically cattle manure was designed. The system produces biogas for domestic use by the households to curb the reliance on paraffin and traditional wood fuel as a mitigation measure to climate change.

### 2.1.1 Feedstock assessment

Quantification of daily farm manure produced is a prerequisite step in proper manure handling and utilization. The manure content of livestock is subject to variation with the digestibility of the ration, animal age, amount of feed and water given to the animal, the amount of bedding used, in addition to the amount of water used to remove manure from the buildings. The manure production of livestock mainly depends on the feedstock the animals are fed on and the water portions they receive [20].

Table 2. 1 below shows the estimated waste production of a few selected livestock at different age ranges for cattle and body weights for pigs and chicken [20].

**Table 2. 1: Livestock waste production**

| **Cattle (months)** | **Waste (kg/day)** | **Pigs (weight)** | **Waste (kg/day)** |
|---|---|---|---|
| Calf (0-6) | 6 | Piglet (15kg) | 1.04 |
| Store (6-15) | 14 | Weaner (30kg) | 4.4 |
| Dairy (6-15) | 14 | Growing-Finishing (70kg) | 5.8 |
| Beef (15-24) | 21 | Growing-Finishing | 5.8 |
| Dairy (15-24) | 21 | Dry Sow (125kg) | 4.03 |
| Beef Cow (24+) | 41 | Sow & Litter | 14.9 |
| Dairy Cow (24+) | 47 | Boar (160kg) | 4.9 |
| **Chickens (weight)** | | **Chickens (weight)** | |
| Layers (1.8kg) | 0.1 | Broiler (0.9kg) | 0.06 |

*Source: Caslin Barry, 2009*

Although the livestock can live to the estimated manure production level shown in Table 2. 1 above, not all the produced livestock manure is recoverable for use, and according to national resources conservation service, only 90 - 95 % of the manure is recoverable under the best circumstances [21]. The deviation from 100 % recoverable manure is attributed mainly to the time the animals are retained in confinement; however, the facility location (climate), the confinement area, and the manure collection methods used are also important factors for the deviation [21].

## 2.2 Anaerobic Digester Systems

Since 17th century when people first got to know about the existence of naturally produced biogas, ways of tapping this energy resource have been investigated with actual biogas systems construction commencing in the mid-19th century [4]. Advances in biogas systems over the decades are notable with much research on optimization of biogas production still at laboratory level.

Any organic matter can be used for biogas production by microbial anaerobic digestion processes. For instance, livestock farming residues, food processing industries, waste water treatment sludge, and other organic wastes. Anaerobic digesters are designed and engineered using different variants and process configurations for their effective operation [22] [23] [24]. The following section gives a detailed discussion on some of the key features of anaerobic digestion and biogas production

### 2.2.1 Anaerobic digestion

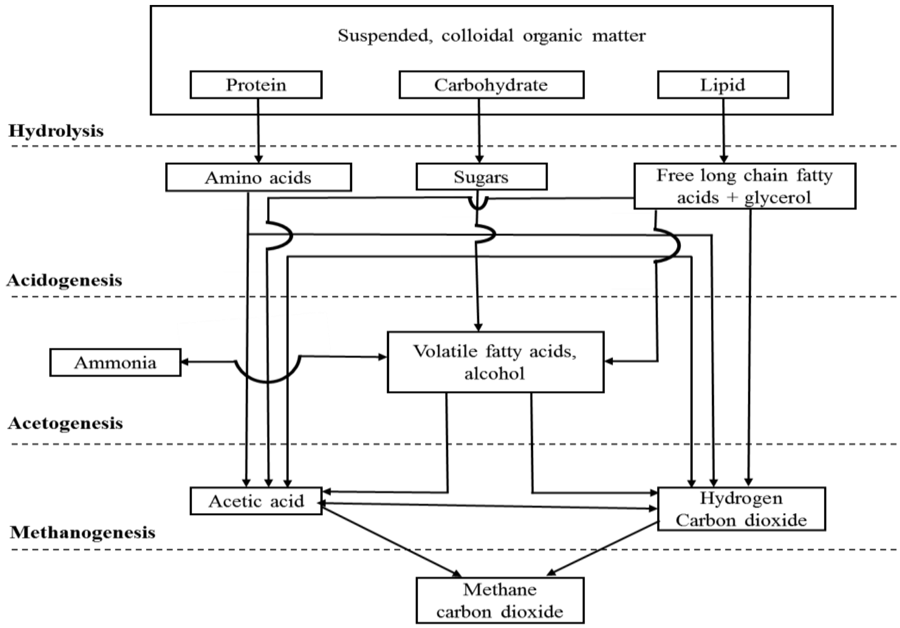
Anaerobic microbiological decomposition is scientifically defined as a process in which micro-organisms derive energy and grow in an oxygen-free environment by metabolizing organic material resulting in production of methane ($CH_4$) and carbon dioxide ($CO_2$) [25].

Organic substances in the anaerobic digester feedstock influent can be subdivided into the following organic compounds: carbohydrates, proteins, lipids and inert material. These organic classes of compounds can be broken down to form biogas, except the inert material which cannot be chemically or biologically digested, and typical examples include among others; sand, stones and heavy metals that could be found in the feedstock.

The breakdown of complex organic substances (carbohydrates, proteins and lipids) by the micro-bacterial community inside the anaerobic digester can be sub divided into four phases with each requiring its own characteristic group of micro-organisms [25]:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

A schematic flow diagram of the different organic compounds and the four steps of the anaerobic digestion process are illustrated in Figure 2. 3 below [25].




*Source: de Mes T. Z. D. et al., 2003*

**Figure 2. 3: Simplified schematic representation of the anaerobic degradation process**

### 2.2.1.1 Hydrolysis

Complex organic polymeric materials have to be broken down to soluble compounds for microorganisms to act upon them. Hydrolysis is the starting step of anaerobic degradation in which organic polymers solubilize into simpler and more soluble intermediates which can then pass through the cell membrane [26]. The yielded simple molecules provide energy and synthesize cellular components in the cells. Since hydrolysis involves material dissociation in water, it is also referred to as liquefaction. The overall hydrolysis rate depends on organic material size, shape, surface area, biomass concentration, enzyme production and adsorption [27].

### 2.2.1.2 Acidogenesis

Acidogenesis also known as fermentation, follows the hydrolysis phase. It is an anaerobic acid producing microbial process without an additional electron acceptor or donor [28]. The monosaccharides and amino acids resulting from hydrolysis are degraded to a number of simpler products such as volatile fatty acids (VFA) including propionic acid ($CH_3CH_2COOH$) and butyric acid ($CH_3CH_2CH_2COOH$) as well as acetic acid ($CH_3COOH$). There are different pathways of monosaccharides degradation leading to different products such as VFA, lactate, and ethanol with different yields of energy [27].

#### 2.2.1.3 Acetogenesis

Acetogenesis follows after acidogenesis. It involves electron acceptor such as $CO_2$ or hydrogen ion oxidising organism, normally bacteria for the conversion of anaerobic acids generated during acidogenesis to acetate, carbon dioxide and hydrogen. This phase is an important intermediate step in biogas production since acidogenesis products cannot be used by methanogens directly. Acetogens are hydrogen producers and while depending on a low hydrogen partial pressure, they maintain a syntrophic (mutually beneficial) relationship with hydrogen-consuming methanogenic archaea [24].

#### 2.2.1.4 Methanogenesis

Methanogenesis involves the conversion of fermentation products such as acetate and $H_2/CO_2$ to $CH_4$ and $CO_2$ by methanogenic archaea. Other methanogens can grow on one-carbon compounds such as methanol and methylamine. Methanogens are substrate specific and only some can utilise a given substrate [24].

### 2.2.2 Anaerobic digestion start-up

Successful anaerobic digestion requires start-up time and careful management of the digester. Digester star-up has three key factors influencing its success, namely; good planning, continuous monitoring and slow changes. This section discusses some of the key precautions for successful digester start-up.

#### 2.2.2.1 Seeding

Anaerobic digestion seed may include raw sludge and digested solids. Digested solids are more preferred though raw sludge can also be used where there is no operating digester in the plant's vicinity. Raw sludge includes animal manure, agricultural waste and household waste.

Fresh cattle manure utilization as digester seed is important because it constitutes a consortium of microbes that undertake digestion activities. Alternatively, a digester can be seeded with an inoculum constituting of secondary and primary sludge in 1:10 ratio. Secondary sludge cannot independently be used as seed since it is comprised of facultative anaerobes while primary sludge contains both facultative anaerobes and methane-forming anaerobes. During the start-up period of the digester, a specific daily amount of fresh manure is added to the digester until improved efficiency is attained by the system [29].

#### 2.2.2.2 Loading

During the start-up period, digester pH control is paramount and should be maintained in 6.8 – 7.2 range and feeding should be done slowly with careful monitoring. To maintain the desired pH, different alkalis could be added. When the digester pH is 7.2 or lower, $NH_4^+$ is favoured while for pH of greater than 7.2. $NH_3$ is favoured [29].

#### 2.2.2.3 Digester stability

The digester may approximately require one month to achieve steady-state. Once the digester has attained stability, evaluation of the biogas production and gas concentrations can be done [29].

## 2.3 Anaerobic Digester Types

Anaerobic digesters can be distinguished in two basic types:

- Batch type reactor
- Continuous type reactor

### 2.3.1 Batch reactor

In batch reactors, the fermentation slurry exhibits temporally staggered sequences. For the batch-type digesters organic material is fed to the digester and allowed to digest and at completion of the digestion process, the effluent is withdrawn from the digester and the process is repeated [24]. batch reactors may or may not include stirring of the digester sludge [30] [31]. Its advantages over the other reactors include: ease of operation, absence of mechanical mixing, and high removal efficiency of an individual contaminant [31].

#### 2.3.1.1 Sequencing batch reactors (SBR)

SBR are fill and draw mode discontinuously operated reactors. When the SBR tank is filled with the sludge, the system is allowed a reaction period yielding biogas during which the sludge settles to tank bottom with the solids separating from the effluent liquor. At the end of a specified period, supernatant and the digested substrate are withdrawn while a small portion is retained in the tank acting as inoculate the incoming feed [24].

### 2.3.2 Continuous reactor

In continuous flow reactors, the fermentation slurry is completely mixed and the anaerobic digestion processes proceed spatially as well as temporally in parallel steps. Digester slurry is constantly or regularly introduced to the digester while the digestate is pulled out either mechanically or by the force of the new feed pushing it out. In continuous digesters, biogas production is not interrupted by loading influent and unloading effluent [24].

Continuous digesters include the following main basic models [24] [30].

- Plug Flow Reactor Model (PFR)
- Continuous Stirred-Tank Reactor Model (CSTR)
- Up flow anaerobic sludge blanket reactors (UASB)

#### 2.3.2.1 Plug Flow Reactor (PFR) model:

Plug flow reactor is also known as Tubular Flow Reactor (TFR). In a PFR, an influent sludge is introduced continuously at one end of the reactor while an effluent digestate exits continuously at the opposite end of the reactor. The PFR does not include sludge mixing but only the flow from one end to the other of the reactor, thus microorganisms activity changes over the reactor length. Mixing only occurs due to friction on the reactor walls. PFR is advantageous in that it is very efficient in individual contaminant removal from the reactor, such as ammonium and trace organics, is possible [31]. In cases where heat transfer is required, individual tubes are jacketed or shell and tube construction is used [30].

#### 2.3.2.2 Continuous Stirred Tank Reactor (CSTR) Model:

CSTR is also referred to as completely mixed reactors, its operation involves continuous influent slurry introduction to the reactor and continuous digestate effluent withdrawal from the reactor. In a CSTR, microorganisms continuously grow replacing microorganisms that are withdrawn with the effluent. In a well-mixed CSTR, the digester sludge concentrations and microorganisms' distribution are uniform throughout the reactor. Therefore, the substrate concentrations and microorganisms in the effluent stream are the same as those respective concentrations within the reactor [31]. The residence time of digester sludge is obtained by simply dividing the volume of the tank by the average volumetric influent sludge rate to the tank [30]. In CSTR, the solids retention time (SRT) is equivalent to the hydraulic retention time (HRT) since there is no stratification [24].

At steady state of CSTR, the influent sludge rate is equal the effluent rate and all calculations performed with CSTRs assume perfect mixing [30].

#### 2.3.2.3 Up flow anaerobic sludge blanket reactors (UASB) model

UASB reactors belong to the category of the high-rate anaerobic reactors. The term "high-rate" describes reactor configurations that result in big differences between the SRT and the HRT by providing significant retention of active biomass. UASB operates at relatively short HRTs, often in the order of two days or less [24].

### 2.3.3 Anaerobic digester design and sizing

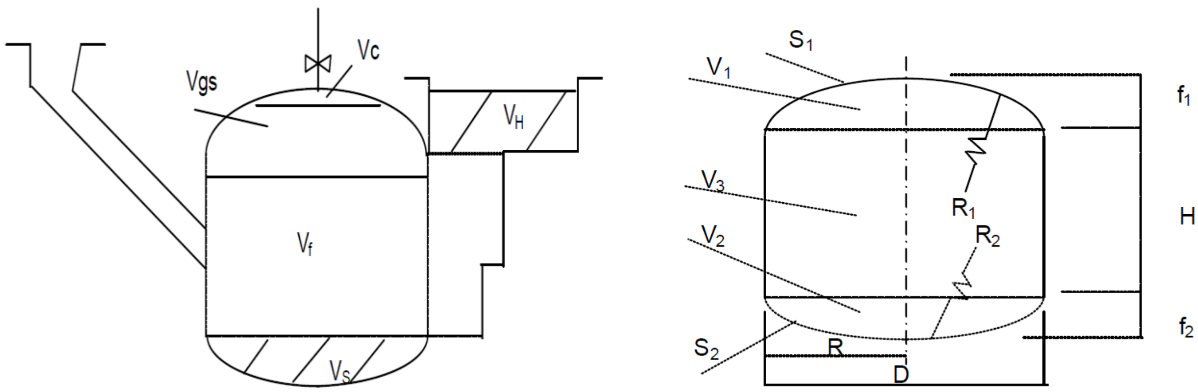
Anaerobic digesters can be designed based on the total solids content (TS) of the digester influent substrate, that is, either operating at a high total solids content (TS > ~20 %), referred to as dry digester reactor, or at a low solids concentration (TS <~20 %), referred to as wet fermentation systems [24].

Solids and slurry waste because of their low total solid content, they are mainly treated in continuous flow stirred tank reactors (CSTR), while soluble organic wastes because of high total solid content, they are treated using high-rate biofilm systems such as UASB reactors [27].

#### 2.3.3.1 Digester design and sizing

Anaerobic digesters are rectangular, cylindrical, or egg-shaped. However, rectangular digesters are no longer used because of the difficulty in mixing the fermentation slurry. The cylindrical shape is the commonly used worldwide. The digester is usually made of concrete, although steel digester designs are also common in smaller sizes [32].

Cylindrical digesters are covered to contain odours, maintain operating temperature, maintain anaerobic condition, and collect digester gas. The anaerobic digester comprises of the following chambers; gas collector, gas storage, fermentation and sludge chambers. The cross-section and geometrical dimensions of the cylindrical shaped biogas digester body are shown in Figure 2. 4 a) and b) below, respectively [33]:




a) b)

*Source: Bio-gas project, 2016*

**Figure 2. 4: Cylindrical shaped biogas digester body: a) Cross-section and b) Geometrical dimensions**

Volume of the digester chambers can be determined using the following equations.

$$V_1 = V_c + V_{gs} \quad (2.\ 1)$$

$$V_2 = V_s \quad (2.\ 2)$$

$$V_3 = V_f \quad (2.\ 3)$$

Where:

$V_c$ is volume of gas collecting chamber

$V_{gs}$ is volume of gas storage chamber

$V_f$ is volume of fermentation chamber

$V_H$ is volume of hydraulic chamber

$V_s$ is volume of sludge layer

For appropriate sizing of a cylindrical biogas digester, the following assumptions shown in Table 2. 2 below can be considered [33].

**Table 2. 2: Assumptions for sizing a cylindrical biogas digester**

| **For Volume** | **For Geometrical Dimensions** |
|---|---|
| $V_c \leq 5\% \; V$ | $D = 1.3078V^{1/3}$ |
| $V_s \leq 15\% \; V$ | $V_1 = 0.0827D^3$ |
| $V_{gs} + V_f = 80\% \; V$ | $V_2 = 0.05011D^3$ |
| $V_{gs} = V_H$ | $V_3 = 0.3142D^3$ |
| $V_{gs} = 0.5(V_{gs} + V_f + V_s)\kappa$ ,<br><br>Where:<br>$\kappa$ is gas production rate per $m^3$ digester volume per day<br>$V$ is digester volume [$m^3$]<br>$V_{gs} + V_f$ is working volume of the digester [$m^3$] | $R_1 = 0.725D$ |
| | $R_2 = 1.0625D$ |
| | $H = 0.40025D$ |
| | $f_1 = {}^{D}/_{5}$ |
| | $f_2 = {}^{D}/_{8}$ |
| | $S_1 = 0.911D^2$ |
| | $S_2 = 0.8345D^2$ |

*Source: Bio-gas project, 2016*

If the digester is stirred to ensure uniform mixing of the slurry, the sludge layer volume $V_s$ is included in the working volume, thus $V_{gs} + V_f + V_s$ covering about 95 % of the digester volume and 5 % of digester volume left for gas collecting chamber.

Digester cover is either classified as fixed or floating. Fixed covers are shaped as either dome-shaped or flat and could be fabricated out of reinforced concrete, steel, or fibreglass-reinforced polyester (FRP). Since concrete roofs are prone to cracking, they are often lined with polyvinyl chloride (PVC) or steel plate to contain gas. Floating covering float over the digester slurry allowing the digester volume to change without allowing entry of air to the digester to mix with the gas [32].

### 2.3.3.2 Digester mixing

To prevent formation of a surface scum layer and deposition of suspended matter on the bottom of the digester, mixing is very crucial. Though natural mixing occurs by the rising of gas bubbles and by influent introduction, auxiliary mixing is required to optimize performance. Mixing methods used include external pumped recirculation, mechanical mixing and gas mixing [32].

### Pumped recirculation

Externally mounted pumps are used to withdraw sludge from the digester and reinject it through nozzles at the bottom of the digester and near the surface to break up scum accumulation.

Though it allows for external heat exchangers to heat the digester, its disadvantages including impeller wear from grit in the sludge, plugging of pumps by rags, and bearing failures [32].

**Mechanical mixing**

It is performed by low-speed flat blade turbines or high-speed propeller mixers. Propellers drive sludge through a draft tube to promote vertical mixing and the draft tube could be internally or externally mounted. This mixing provides good mixing efficiency and breaks up any scum layer, however, rags in sludge could foul the impellers [32].

**Gas mixing**

The produced gas in the digester injected into the sludge to foster mixing. This approach has four variations of mixing anaerobic digesters [32]:

- Confined injection of gas bubbles intermittently at the bottom of pistons to create piston pumping action and surface agitation.

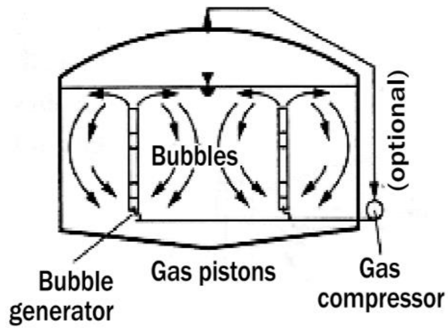
  Gas bubbles rise up the tubes and act like pistons, pushing the sludge to the surface. This approach requires low power and is effective against scum build-up.
- Confined release of gas within a draft tube positioned inside a digester.

  The acts as a gas lift pump, causing the flow of sludge entering the bottom of the tube to exit at the top. It induces bottom currents and prevents accumulation of settleable material.
- Unconfined injection of gas through a series of lancers suspended from the digester cover.

  Gas injection pipes are located throughout the digester and gas discharge continuously through all lances or sequentially by the use of a rotary valve and pre-set timers. Though it is very effective against scum build-up, there is a greater chance of solid deposition resulting due to less efficient mix regime.
- Unconfined release of gas through a ring of diffusers mounted on the floor of the digester.

  Gas is discharged continuously through floor-mounted diffusers. It is effective against solid build-up. However, it is not effective against scum build-up.

In this study, a gas piston mixing approach was considered for digester fermentation slurry mixing. Figure 2. 5 below shows the schematic of a digester with a gas piston mixing system [32].




*Source: Turovskiy I. S. & Mathai P. K., 2006*
**Figure 2. 5: Anaerobic digester with a gas piston mixing system**

It is assumed that the velocity of the fermentation slurry as a result of digester mixing by injecting the gas is considerably so low such that the system is referred to as operating in a natural convection condition.

## 2.4 Factors Affecting Anaerobic Digestion

Many factors affect the performance of anaerobic digester processes. These hindering factors range from digester process factors such as the solid retention time, organic loading rate and hydraulic loading rate to environmental factors with in the digester such as temperature, pH, nutrient supply, and the presence of toxics to operational factors of the digester such as mixing and the characteristics of the waste being treated [24]. Some important factors are discussed in the following section.

### 2.4.1 Temperature

Anaerobic processes are affected by temperature like any other biological processes. Temperature affects the physical-chemical properties of all components in the digester (e.g. viscosity and surface tension) as well as the kinetic and thermodynamic behaviour of the biological processes in the digester [27]. Anaerobic digestion can be operated in a wide range of temperatures and the growth rate of microbes in the anaerobic digester is temperature dependent.

Anaerobic digestion can occur at temperatures as low as 0 °C, however, the rate of methane production is very low and only increases with increasing temperature until a relatively maximum temperature is reached. The relation between energy requirement by the system for heating it and its corresponding biogas yield determines the choice of digester temperature [34]. Anaerobic bacteria are categories in three temperature diapason groups namely; psychrophiles (< 20 °C), mesophiles (20 – 40 °C), thermophiles (45 – 70 °C) [27] [35].

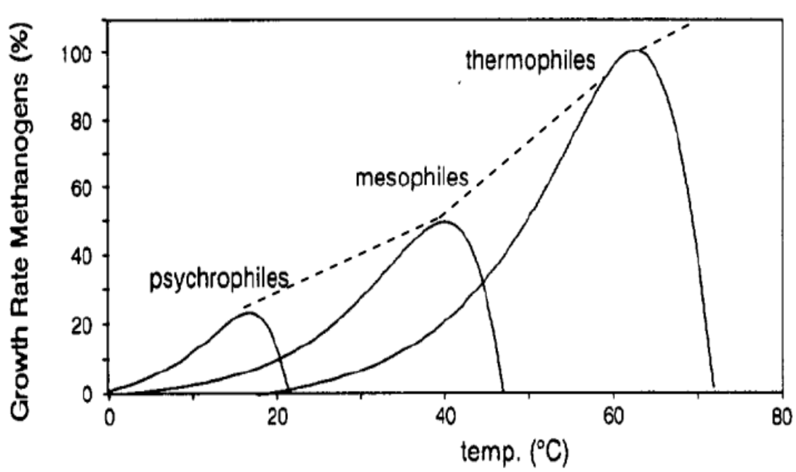
Digester temperatures below the optical diapason level have a greater impact on the microorganism growth rate compared to temperatures above the optimal level. Table 2. 3 below shows the temperature ranges for optimal microorganism growth in a digestion process [36].

**Table 2. 3: Temperature ranges for optimal microorganism growth**

| **Temperature Diapason** | **Temperature** (℃) | |
|---|---|---|
| | **Range** | **Ideal** |
| Psychrophilic | -10 to 30 | 12 to 18 |
| Mesophilic | 20 to 50 | 25 to 40 |
| Thermophilic | 35 to 75 | 55 to 65 |

*Source: Marco V. S. & Carlos A. L, C., 2006*

It can be observed from Table 2. 3 above that the temperature diapasons of anaerobic digestion overlap. Figure 2. 6 below shows the three temperature diapasons of methanogenic microbes each having an optimal growth rate; with the dotted line showing an approximated exponential increase in metabolic activity at increasing temperature [35].




*Source: Buysman E., 2009*

**Figure 2. 6: Relative growth rate of psychropiles, mesophiles and thermophiles**

Psychrophilic anaerobic conditions are characterized by lower methane production rates in the digester. Psychrophilic anaerobic conditions require extended solids retention times (SRT) and smaller influent sludge rates [24].

At any instance, when the digester temperature shifts from the mesophilic diapason to the psychrophilic diapason, the microbial population can still exhibit very similar composition with a large number of mesophiles remaining active despite the low metabolic rates which indicates that psychrotolerant rather than psychrophilic microorganisms are involved [24].

Thermophilic anaerobic degradation exhibits opposite characteristics to the psychrophilic digestion degradation. Thermophilic anaerobic processes exhibit higher temperature allowing higher loading rates, shorter SRT, microbes growth is very fast and methane production is higher with specific methane production rates of 50 - 100 % higher than for mesophilic anaerobic digestion [31]. It is also advantageous given the pathogen inactivation at higher temperatures and require smaller reactor sizes due to the shorter SRT [31].

In biogas power plants, only the mesophilic and thermophilic ranges are used in operational anaerobic digestion systems and the digesters run at around 35 °C and 55 °C respectively. However, in absolute terms the optimal temperature may depend on the exact type of feedstock material undergoing treatment. Furthermore, it is noted that any AD process for biogas production requires a relatively constant temperature to progress at its greatest efficiency [37].

Osman A. A., et al. (2015) noted that, though 35 – 37 °C range is often suggested for manure digester systems, the digesters require a significant amount of additional heat energy to sustain the digester operating temperatures at these levels. In their study, they concluded that operating a digester at 22 °C and 28 °C results in about 70 % and 87 % methane production respectively, of the value from a digester operating at 35 °C. Thus, the digestion process differs in the rate of microorganism growth and methane production rates [38].

Bandara W. et al. (2012) asserted that operating a digester under mesophilic diapason (30 °C – 40 °C), notable energy input is required to heat the influent which results in energy loss. Thus, operating anaerobic digester at ambient temperature in temperate regions offers economic advantage over the operation under mesophilic or thermophilic conditions [39]. Depending on the digester organic loading rate, an average of 59 – 62 % COD can be removed from the substrate in the temperature rate of 10 – 20 °C [40]. During digester feeding, the digester temperature drops because the influent flows in at a lower temperature to that of the digester sludge [32].

Digester operating temperature is influenced by the exothermal microbial activity on the organic fermenting sludge and to a larger extent by the ambient temperature which is transferred through its walls. Ambient temperature of any given place is not constant but varies over time yet the digester temperature does not drastically change but gradually over time. On average, the digester temperature is always close to the ambient temperature for digesters without heating systems incorporated to them that are constructed above the ground [41].

Lutaaya Fred (2013) noted that digester operating temperature for biogas digesters in Uganda ranges from 18 °C to 25 °C, psychrophilic range. Cases where digester temperature was slightly lower than the ambient temperature were recorded in the study as shown in Table 2. 4 below of the sampled digesters in different regions of Uganda [42].

**Table 2. 4: Anaerobic digester operating temperature and ambient temperature for digesters in different regions of Uganda**

| Digester Plant | Region | Temperature | |
|---|---|---|---|
| | | Ambient Temperature (℃) | Digester Temperature (℃) |
| Digester 1 | Kampala | 24 | 23.4 |
| Digester 2 | Mukono | 25 | 23 |
| Digester 3 (fed with pig dung) | Mukono | 30 | 24 |
| Digester 4 | Jinja | 26 | 22.8 |
| Digester 5 | Wakiso | 21.8 | 21.4 |
| Digester 6 | Mbale | 18.3 | 20.5 |
| Digester 7 | Luwero | 21.9 | 23.4 |
| Digester 8 | Wakiso | 27.8 | 22.6 |
| Digester 9 | Jinja | 19.4 | 19.2 |

*Source: Lutaaya F., 2013*

Digester systems for underground implementation in the tropics utilize geothermal heating rendered by the soil temperature and as an insulation mechanism to stabilize the digester operating temperature. The soil temperature regimes of tropical environments are characterized by a greater constancy of soil temperatures and a greatly reduced annual variation in the soil temperature. The mean soil temperature at low elevations near the equator is relatively constant at about 25 ℃ throughout the year with winter temperatures less than 20 ℃ not common in many tropical areas [43].

The average soil temperature for equatorial regions can be obtained from altitude and soil temperature relationships shown in Equations (2. 4) and (2. 5) below [44]:

Grassland/Bushland: $$T(z) = 33.8 - 6.84z \quad (2.\ 4)$$

Forest: $$T(z) = 27.6 - 5.34z \quad (2.\ 5)$$

Where $z$ is altitude in kilometers.

The designed digester system in this study, however, is an above-ground digester system with insulation to minimize temperature variations within the digester system to stabilize the microorganism activity and gas production.

### 2.4.2 pH

For classification of a substance as either acidic or basic, the pH method of expression was developed. pH is defined as the negative logarithm of the hydrogen-ion (H+) concentration and representing an important characteristic of chemical species since it affects equilibria between most chemical species [24].

pH greatly impacts the enzyme activity in microorganisms which is fundamental for metabolism, thus influencing the optimal growth of each of the microbial groups involved in anaerobic degradation. Enzyme activity is enhanced to its maximum at its optimal pH only within a specific pH range which varies for every group of microorganisms; for methanogenic archaea, the optimal pH lies in very narrow interval of 5.5 - 8.5 and for the acidogens, pH varies from 8.5 down to 4. The optimum pH for the acetogens and methanogens around 6 and 7, respectively with the methanogens growth rate noted to fall steeply at pH < 6.6 [24].

In anaerobic treatment processes, the pH should be kept close to neutral (6.5-8.0) since acidogens also function at pH close to neutral with methanogens often being the digestion rate-limiting step in anaerobic digestion [27].

### 2.4.3 Internal mixing and retention time

Effective fermentation slurry mixing in the anaerobic digester is critical for the successful operation of an anaerobic process. Poor mixing of the fermentation slurry will lead to stratification and clogging within the digester which results in partially digested sludge being withdrawn from the reactor [45].

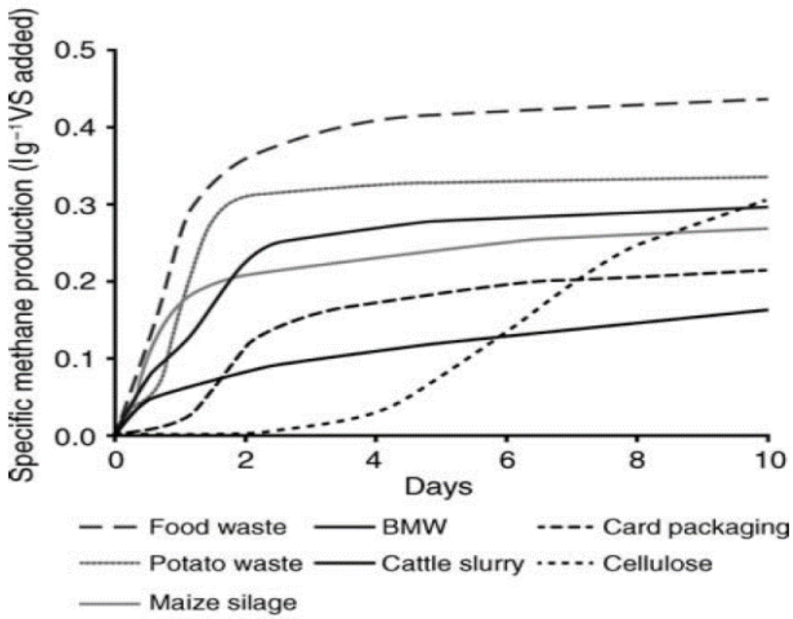
Digesters with short retention times are characterised with high gas production rates since mainly the easily degradable organic substrates are degraded. Regarding the total organic load, short SRTs have poor gas yields because much of the volatile solids are washed out in the digestate effluent and on the other hand, for long retention times the gas yield increases and the gas production rate deteriorates. In addition, it should be noted that there are different specific gas yields for different types of substrate. Generally, the types of microorganisms that can grow in the digestion process are controlled by SRT and thus, influences the degree of organic matter degradation as well as the gas yield of the digester [46] [24].

Figure 2. 7 below shows the specific methane production of organic waste at various retention time obtained using a simple first-order rate Equation (2.6) below [47]:

$$Y = Y_{max}(1 - e^{-kt}) \qquad (2.\ 6)$$

Where

| | |
|---|---|
| $Y$ | is the cumulative methane yield at time $t$ |
| $Y_{max}$ | is the ultimate methane yield |
| $k$ | is the first-order rate constant |
| $t$ | is time |




*Source: Wellinger A. et al., 2013*

**Figure 2. 7: Specific methane yield for different substrates**

Since the substrates are heterogeneous consisting of both rapidly and more slowly degrading fractions, a bet fit can be obtained by assuming that the gas production curve represents these different rates and properties. Thus, methane production is given by Equation (2. 7) below, where $P$ is the proportion of degradable material [47]:

$$Y = Y_{max}(1 - Pe^{-k_1 t} - (1 - P)e^{-k_2 t}) \qquad (2.\ 7)$$

Results of food waste, maize silage and cattle slurry are shown in Table 2. 5 below [47].

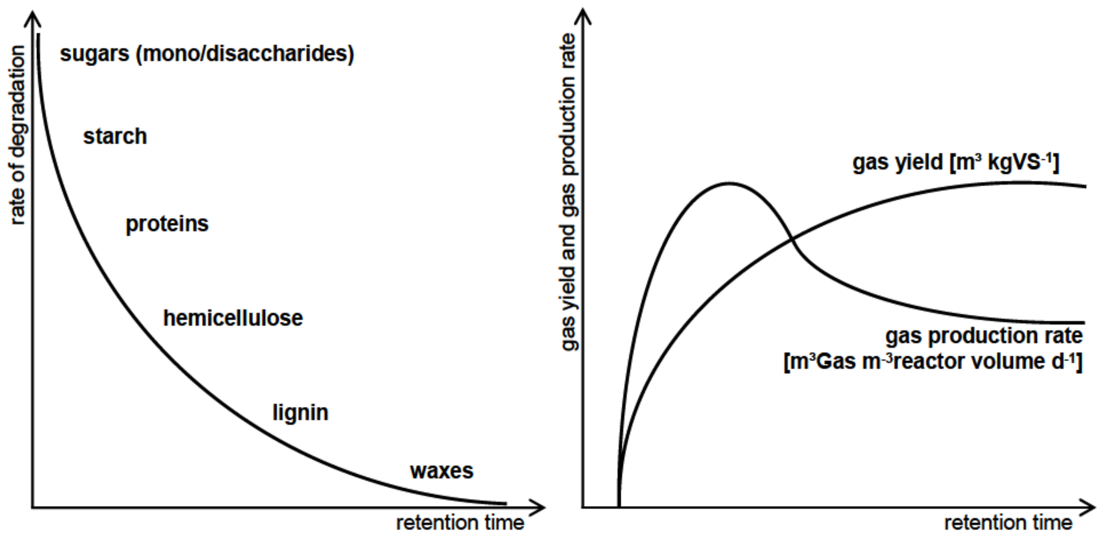
**Table 2. 5: Kinetic parameters from Biochemical Methane Potential (BMP) modelling**

| Parameter Values | Food waste | | Maize silage | | Cattle slurry | |
|---|---|---|---|---|---|---|
| | Eq. (2. 6) | Eq. (2. 7) | Eq. (2. 6) | Eq. (2. 7) | Eq. (2. 6) | Eq. (2. 7) |
| $Y_{max}$ ($L\ CH_4 g^{-1}\ VS\ added$) | 0.470 | 0.470 | 0.345 | 0.345 | 0.260 | 0.260 |
| $P$ | 1 | 0.88 | 1 | 0.60 | 1 | 0.33 |
| $k$ or $k_1$ | 0.73 | 1.02 | 0.44 | 1.50 | 0.09 | 0.50 |
| $k_2$ | 0 | 0.06 | 0 | 0.07 | 0 | 0.05 |
| $R^2$ | 0.9874 | 0.9980 | 0.9703 | 0.9987 | 0.9911 | 0.9978 |

*Source: Wellinger A. et al., 2013*

The $P$ values of 0.88, 060 and 0.33 reflect the relative proportions of readily degradable material in food, maize silage and cattle slurry respectively. The decay constant $k_2$ is approximately the same for all the three cases, but $k_1$ values differ. The $k_1$value for cattle slurry is low because the slurry has already undergone digestion process [47].

Figure 2. 8 below shows the rate of degradation of different types of substrate vs. retention time (left) and gas yield/production rate vs. retention time (right) [46].




*Source: Eder B. & Schulz H., 2006*

**Figure 2. 8: Rate of degradation of different types of substrate vs. retention time (left) and gas yield/production rate vs. retention time**

In completely mixed anaerobic digester systems that do not include solids recycling, both hydraulic retention time (HRT) and the SRT are identical while for digestion systems which involving solids recycling, the SRT is greater than the HRT [48].

### 2.4.4 Organic loading rate

The volumetric organic loading rate (OLR) is used to characterise the loading on anaerobic digesters. OLR is related to the hydraulic retention time (HRT) through the active biomass concentration in the bioreactor. Knowledge of the OLR renders crucial information for the design and dimensioning of the digester since it quantifies the reactor effective volume [24].

OLR also referred to as the influent total volatile solids of the digester can be evaluated in terms of volatile solids (VS) mass applied by using Equation (2. 8) below [24]:

$$OLR = S_0 = \frac{VS \times S_d}{V_D} \qquad (2.\ 8)$$

Where:

$S_0$ is influent total volatile solids ($kgVS.m^{-3}V_D.day^{-1}$)

$VS$ is volatile solid content (%)

$V_D$ is anaerobic digester volume ($m^3$)

HRT is hydraulic retention time (days)

$S_d$ is daily fermentation slurry added (kg)

According to Rittmann and McCarty (2001), the recommended volatile solids loading rate for high-rate anaerobic digestion is 1.6- 4.8 kg per $m^3.VS \cdot day$, and the recommended volatile solids loading rate for low-rate anaerobic digestion (digestion with no heat and no mixing) is 0.5 - 1.6 kg per $m^3.VS \cdot day$ [31].

### 2.4.5 Substrate, nutrients and trace elements

Theoretically, any type of biomass can be degraded to produce biogas, however, growth in biogas technology worldwide has been based upon pig and cattle manure and agricultural wastes. Cattle manure is a preferred digester substrate because of the existence of methanogenic bacteria in the stomachs of ruminants [5].

Biogas yield is dependent upon the biogradable substrate type and its compositions because of the necessity by anaerobic digestion organisms for sources of energy, carbon for new cellular material synthetization, inorganic elements (i.e. nutrients) such as nitrogen, phosphorus, sulphur, and organic nutrients (also termed growth factors) for continuation of reproduction and proper functioning [49] [24]. Chemical conditions within the digester are dependent upon biogradable substrate composition, for instance, the resultant pH and possibility of degradation products and intermediates reaching inhibitory concentrations [24].

Table 2. 6 shows a list of selected biogas substrates commonly used in anaerobic digesters for biogas production [50] [20].

**Table 2. 6: Characteristics and operational parameters of the most important agricultural feed stocks**

| Feedstock | Total Solids TS (%) | Volatile Solids (% of TS) | C:N ratio | Biogas yield ($m^3$/kg VS) | Retention Time (days) |
|---|---|---|---|---|---|
| Pig slurry | 3-8 | 70-80 | 3-10 | 0.25-0.50 | 20-40 |
| Cow manure | 5-12 | 75-85 | 6-20 | 0.20-0.30 | 20-30 |
| Chicken slurry | 10-30 | 70-80 | 3-10 | 0.35-0.60 | >30 |
| Whey | 1-5 | 80-95 | n.a | 0.80-0.95 | 3-10 |
| Leaves | 80 | 90 | 30-80 | 0.10-0.30 | 3-10 |
| Wood shavings | 70 | 95 | 511 | n.a | n.a |
| Straw | 70 | 95 | 90 | 0.35-0.45 | 10-50 |
| Wood wastes | 60-70 | 99.6 | 723 | n.a | n.a |
| Garden wastes | 60-70 | 90 | 100-150 | 0.20-0.50 | 8-30 |
| Grass | 20-25 | 90 | 12-25 | 0.55 | 10 |
| Grass silage | 15-25 | 90 | 10-25 | 0.56 | 10 |
| Fruit wastes | 15-20 | 75 | 35 | 0.25-0.50 | 8-20 |
| Food remains | 10 | 80 | 35 | 0.50-0.60 | 10-20 |

n.a = not available
*Source: Steffen R. et al., 1993; Caslin B., 2009*

Anaerobic substrate input into the digester is commonly evaluated in terms of total chemical oxygen demand (COD) or total volatile solids (VS) since not all the substrate components are biogradable. The available biogradable substrate fraction of the total volatile solids can be distinguished from the total anaerobic digester substrate input. A linear relationship in Equation (2. 9) below between the biodegradability and the lignin content of substrate can be used given one of the variables [51].

$$B = 0.83 - 0.028x \qquad (2.\ 9)$$

Where $B$ is the biodegradable fraction (% of VS) and $x$ the lignin content (% of VS). By using this formula with ideal gas law, considering an average of 1.4 kg COD/kg VS conversion [52], and a 65% methane content of biogas, the ultimate methane recovery from selected wastes was calculated and compared with the value of GTZ [53], of a dome digester with a retention time of 25 days at a temperature of 30 ℃ as shown in Table 2. 7 below [35].

**Table 2. 7: Calculated biodegradability and methane yields of fresh manure**

| **Fresh manure source** | **VS** (%) | **Lignin** (% of VS) | **Biodegradable fraction** (% of VS) | **Maximum methane production** (L $CH_4$/kg) | **Calculated Methane yields** (**GTZ** [53]) (L/kg VS) |
|---|---|---|---|---|---|
| **Cow & Buffalo** | 13 | 7.9 | 61 | 319 | 98-228 |
| **Pig** | 12 | 2.2 | 77 | 402 | 221-358 |
| **Poultry** | 17 | 3.4 | 73 | 384 | 202-403 |

*Source: Buysman E., 2009*

It is shown in Table 2.7 above that depending on the feedstock, that practical methane yields never reaches the theoretical maximum methane yield. Maximum methane recovery in anaerobic digester cannot be achieved due to several constraining factors such as a retention time and suboptimal conditions for microbial activity; optimal conditions would be, the right temperature, amount of mixing, the right quantity of nutrients, the right pH and C: N ration for the microbes and sufficient hydraulic retention time (HRT) and substrate retention time (SRT) [35].

Excess of either carbon or nitrogen in the digester substrate hinders the digester performance resulting in production of biogas with high carbon dioxide content; straw and urine are some of the examples of biomass resources with high carbon and nitrogen levels respectively [5]. Carbon sources and nutrient availability in the digester sludge are required for effective volatile solids biodegradation. Nitrogen and phosphorous are the most important nutrients in suggested ratios of C: N = 10:1 to 30:1, N: P = 5:1 to 7:1 as well as COD: N: P = 420:7:1 to 1500:7:1 [46] [45].

### 2.4.6 Foreign materials

Anaerobic digestion process is significantly affected by the presence of foreign materials such as animal bedding, sand and silt that could be carried along with the animal manure. For instance, the Monroe, WA dairy digester poor performance is attributed to the use of cedar wood chip bedding [54]. Thus, the quality and quantity of the bedding material added to the manure applied to the digester will have a significant impact on its operation. Silt and sand should be removed before manure is introduced to the digester.

## 2.5 Biogas Composition

Biogas is a mixture of predominantly methane and carbon dioxide, however, it also constitutes some other gases, such as hydrogen sulfide (a potential dangerous gas) and ammonia.

Biogas is typically composed of 50 to 65 % (volume) $CH_4$ and 35 to 50 % (volume) $CO_2$ as detailed in Table 2. 8 below [55] [56] [35].

**Table 2. 8: Typical biogas components**

| Gas | Formula | Unit | Prevalence |
|---|---|---|---|
| Methane | $CH_4$ | % | 50-65 |
| Carbon dioxide | $CO_2$ | % | 35-50 |
| Hydrogen sulfide | $H_2S$ | $g/m^3$ | 4-6 |
| Ammonia | $NH_3$ | % | 0-0.05 |
| Humidity | $H_2O$ | $g/m^3$ | 30-160 |

*Source: Buysman E., 2009; Prakash P., 2011; Nijaguma B. T., 2002*

The above fluctuations in the biogas composition are as a result of the quality of influent feedstock, as well as different population numbers of the microbials in the digesters, which are largely affected by the environment and the operating conditions.

Biogas has distinct physical characteristics, such as energy content, ignition temperature, density, critical pressure and critical temperature as depicted in Table 2. 9 below with their corresponding values [35].

**Table 2. 9: Physical characteristics of biogas**

| Characteristics of biogas | Value |
|---|---|
| Energy content | 20 - 25 $MJ/m^3$ |
| Ignition temperature | 650 - 750 ℃ |
| Density | 1.2 $kg/m^3$ |
| Critical pressure | 75 - 89 bar |
| Critical temperature | 190.65 K (-82.5 ℃) |

*Source: Buysman E., 2009*

## 2.6 Dilution of Fermentation Slurry

High total solid (TS) contents of slurry fed into the digester could change the fluid dynamics of substrates. Such high concentrations often cause digester process failure because of bad mixing behavior, failed pumping, solids sedimentation, clogging and scum layer formation. As a rule of thumb for conventional continuous stirring tank reactor (CSTR) - digester types, the optimum TS - concentration should be in the range of about 6 - 10 % [50].

Standard pumps of significantly low energy requirement are often used for influent transportation in low total solids digesters. Such pumps require more volume and area because of the increased liquid-to-feedstock ratio [24]. The required slurry dilution water $W_s$ to attain the desired low total solid content in the anaerobic digester slurry concentration $S_D$ for ease of pumping in CSTR digester can obtained using Equation (2. 10) below:

$$W_s = \frac{(TS - S_D) \cdot S_d}{S_D} \quad (2.\ 10)$$

$$S_d = {}^{V_D}/_{HRT} \quad (2.\ 11)$$

Where:

- $W_s$ is slurry dilution water $(kg)$
- $S_D$ is desired slurry TS concentration (%)
- $S_d$ is daily fermentation slurry added $(kg)$
- TS is total solid content of the feedstock (%)
- $V_D$ is digester volume (expressed in kg)

Dilution of the slurry reduces the concentration of certain constituents like nitrogen and sulfur that result in the production of products such as ammonia and hydrogen sulfide that inhibit anaerobic digestion process. However, dilution could as well cause stratification within the digester which would necessitate intense mixing to reduce the stratification of dilute waste [54].

Daily amount of influent, $S_f$ for a digester system is thus determined using Equation (2. 11) below:

$$S_f = S_d + W_s \quad (2.\ 12)$$

## 2.7 Methane Production Potential

Biodegradable COD present in organic sludge is preserved in the end products during anaerobic digestion process in form of methane and the newly formed bacterial mass. For cases of complete biodegradability of an organic compound $(C_nH_aO_bN_d)$ and complete conversion by the anaerobic organism into methane, carbon dioxide and ammonia, theoretically, the amount of the gases produced can be evaluated using the Buswell Equation (2. 13) below *[57]*:

$$C_nH_aO_bN_dS_e + \left(n - {}^{a}/_{4} - {}^{b}/_{2} + {}^{3d}/_{4} + {}^{e}/_{2}\right)H_2O \rightarrow \left({}^{n}/_{2} + {}^{a}/_{8} - {}^{b}/_{4} - {}^{3d}/_{8} - {}^{e}/_{4}\right)CH_4 + \left({}^{n}/_{2} - {}^{a}/_{8} + {}^{b}/_{4} + {}^{3d}/_{8} + {}^{e}/_{4}\right)CO_2 + dNH_3 + eH_2S \quad (2.\ 13)$$

### 2.7.1 Food to microorganism ratio

The food to microorganism ratio also known as kinetic parameter $(K)$ is the key factor controlling anaerobic process. At a given temperature, the bacteria consortia in the digester can only consume a limited quantity of volatile solids each day. Food to microorganism ratio is the ratio of volatile solids concentration supplied to the bacteria concentration in the digester. A lower $K$ results in a greater percentage of waste conversion to gas [54].

It would be easier to determine $K$ if all of the influent volatile concentration is converted to gas. However, it is never the case and the bacteria concentration is difficult to measure since it is difficult to differentiate the bacteria concentration from the influent waste [54]. The value of parameter $K$ can be determined by the experimentally established Equation (2. 14) below, which shows no significant impact of digester temperature on $K$, but an exponential relation with $S_0$ [58]:

$$K = 0.8 + 0.016e^{(0.06S_0)} \quad (2.\ 14)$$

$S_0$ is the influent total volatile solids (TVS) concentration, (kg $\mathrm{VS/m^3 influent/day}$).

It is noted that an increase in kinetic parameter $K$ increases chances of inhibition of fermentation process, that is, the fermentation slurry could digest in unrelaxed and unnatural way because of digester overloading symbolizing addition of more substrate in the digester that exceeds what the bacteria can act on effectively [58].

The value of kinetic parameter $K$ should be in the following ranges shown in Equations (2. 15) and (2. 16) below for the respective livestock for safety and effective operation of the digester [59];

$$K_{cattle} \leq 1.64 \quad (2.\ 15)$$

$$K_{swine} \leq 1.2 \quad (2.\ 16)$$

### 2.7.2 Methane production rate

According to Axaopoulos P. (2001), a key parameter needed to calculate the methane production ($\gamma_0$), the main constituent of biogas process from anaerobic fermentation of waste, is the kinetic parameter $K$ [60]. According to Hill (1982b) any slight increase in $K$ results in a notable decrease of $\gamma_0$ [61].

The methane production rate $\gamma_0$ ($m^3\ CH_4.m^{-3}$fermentor $\cdot$ day$^{-1}$) can be calculated using the Equation (2. 17) below given by Chen and Hashimoto (1978) [62]:

$$\gamma_0 = \frac{B_0 \cdot S_0}{HRT}\left(1 - \frac{K}{HRT \cdot \mu_m - 1 + K}\right) \qquad (2.\ 17)$$

Where: $B_0$ is the ultimate $CH_4$ yield ($m^3\ CH_4$/kg VS added) and $\mu_m$ is the maximum specific growth rate (day$^{-1}$). The values for $\mu_m$ can be calculated using Equation (2. 18) below [63]:

$$\mu_m = 0.013T - 0.129 \qquad (2.\ 18)$$

Where: T is the digester temperature ranging between 20 and 60℃.

If $B_0$, $\mu_m$, $S_0$ and $HRT$ are kept constant and $K$ increases, the methane production rate $\gamma_0$ decreases. Thus increase in $K$ indicates some type of inhibition has occurred that could be as a result of inhibitory substances like ammonia, volatile acids, heavy metals and salts [63].

Methane yield is more useful and preferred over biogas yield in anaerobic process assessment with most scientific literature reporting yield in terms of methane yield per dry weight of volatile solids. Accurate evaluation of $CO_2$ or $CH_4$ gas production from the digester requires detectors or expensive lab tests like gas chromatography to be attained [64].

The ultimate methane yield, $B_0$ for livestock manures varies based on the livestock species, ration, manure age, manure collection and storage methods as well as the amount of foreign material incorporated in the manure [58].

The ultimate methane yield, $B_o$ of a specific substrate is easily determined using its chemical oxygen demand (COD) characterization, elemental composition or organic fraction composition for reliable results. $B_o$ can be calculated using Equation (2. 19) below with an assumption that the equation is valid for any substance or product [65].

$$B_o = \frac{n_{CH_4} \cdot R \cdot T}{P \cdot VS_{added}} \tag{2. 19}$$

And

$$n_{CH_4} = \frac{COD}{64(g/mol)} \tag{2. 20}$$

Where:

$n_{\mathrm{CH_4}}$ is the amount of molecular methane (mol)

$R$ is the gas constant ($R = 0.082$ atm L/mol K)

$T$ is the temperature (K)

$P$ is the atmospheric pressure (1 atm)

$VS_{added}$ is the volatile solids in the substrate (g)

$COD$ is the chemical oxygen demand of the substrate

Contretas E. M. et al., (2002) experimentally found out that the conversion factor $f_{cv}$ relating COD and volatile solids (VS) ranged between 1.14 and 1.66 and it is not dependent on the dilution rate [66]. However, Adrianus C. et al., (2012) assumes that $f_{cv}$ on average is 1.5 [67]. Equation (2. 21) below is the relationship between COD and VS:

$$COD = f_{cv} \cdot VS \tag{2. 21}$$

In this study, the conversion factor $f_{cv}$ equivalent to 1.2 was used in evaluating the COD in the influent slurry.

### 2.7.3 Volatile solids reduction

Sludge solids reduction is assumed to only take place in the volatile solids portion. Volatile solids reduction in high-rate anaerobic digester ranges from 50 to 65 % and its achievement depends on the sludge characteristics and the digester operating conditions. For high-rate digester systems, the empirical Equation (2. 22) below holds in predicting the volatile solids reduced from the digester sludge [32].

$$VS_R = 13.7In(SRT_d) + 18.9 \qquad (2.\ 22)$$

Where

$VS_R$ Volatile solids reduction (%)

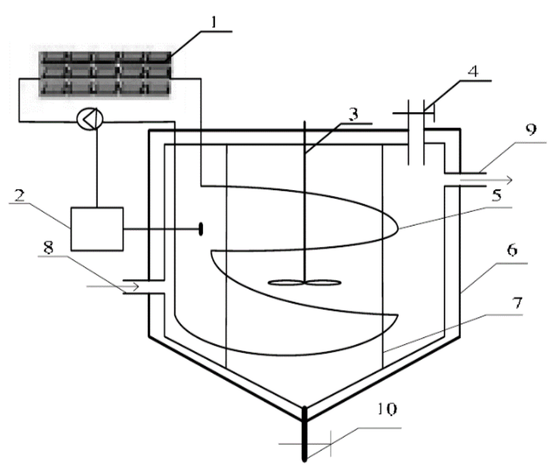
$SRT_d$ Digester design Solid retention time (days)

With the above expression, the volatile solids reduction of an anaerobic digester system can be predicted.

## 2.8 Solar-aided Anaerobic Digester

Till today, solar energy utilization in the anaerobic biological treatment steadily remains a difficult approach because the climate, region, terrain, season, weather, day or night changes vary widely in different conditions. It is a prerequisite when designing a solar energy heating and transfer system to ensure that the system has a high heat exchange efficiency and energy recovery for optimal solar energy utilization as well as a temperature control system to maintain the temperature constant. Heat energy storage is crucial to balance temperature between day and night, sunny and rainy periods and there should be assurance that heat interchanger and pipeline for the circulating system have high heat transfer coefficient and are corrosion-resistant [68].

Figure 2. 9 below shows the design investigation of a solar energy heating and transfer system as proposed by Zhenjie R. et al. (2012) [68].

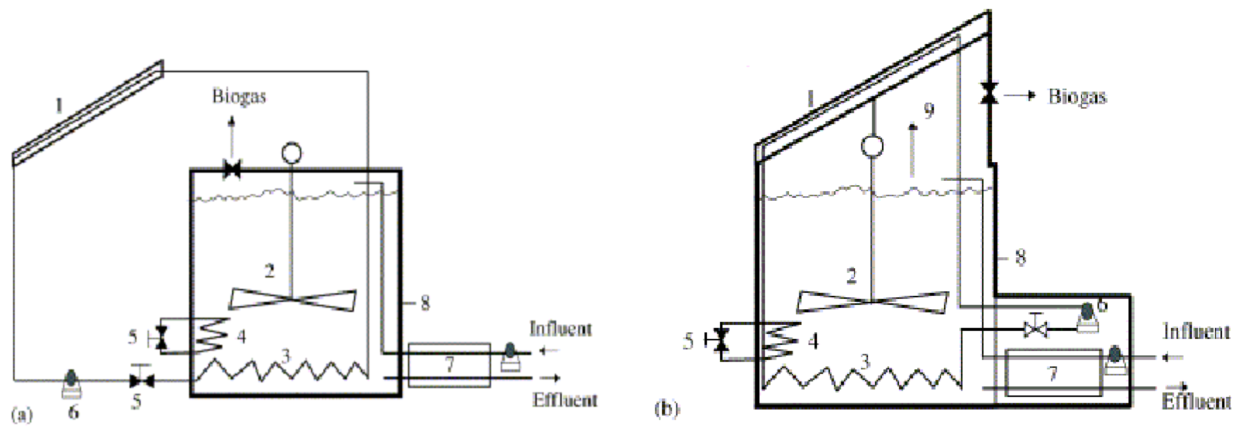



Where 1- Solar Energy Collectors, 2- Temperature Controller, 3- Blender, 4- Relief Valve, 5- Heat Exchanger Tube, 6- Insulating Layer, 7- Bracket, 8- Influent, 9- Effluent, 10- Mud hole

*Source: Zhenje R. et al., 2009*

**Figure 2. 9: Solar Energy Heating Adjustment Pool**

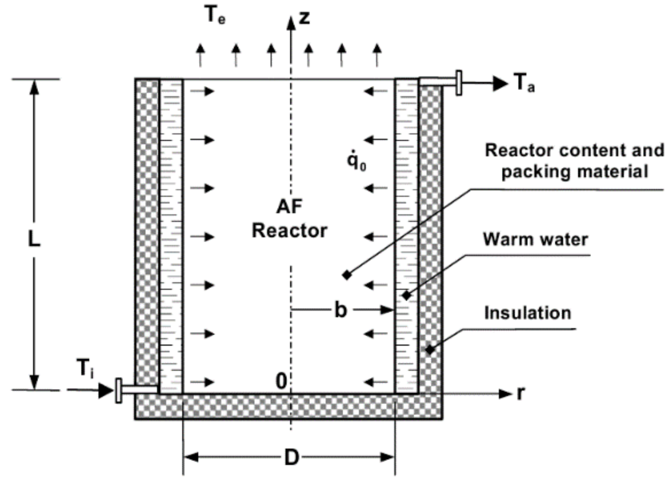
In addition, energy recovery equipment can be utilized to harness energy exchange between the effluent and influent for waste heat can be recovered well [69]. Buysman E. (2009) noted that experiments have been conducted in Egypt to assess the possibility of utilizing solar heating system to heat up a 10 $m^3$ small scale digester to thermophilic temperatures (50$^oC$) [70]. Unique approaches that included use of the effluent heat to heat the influent sludge via a heat recovery system and integration of a solar collector system as part of the digester roof as shown in Figure 2. 10 below were used in addition to extreme insulation of reactors to an average thermal conductivity $k_v = 0.33\ W/m^2.℃$ [35].




*Source: Buysman E., 2009*

**Figure 2. 10: Digester with (a) Separate Solar Collector ; (b) Integrated solar collector system**

Yiannopoulos A. C, et al. (2008) proposed a reactor system where solar energy absorbed by flat plate collectors is transferred to a heat storage tank from which continuous supply to the anaerobic-filter reactor of water at a maximum temperature of 35$^oC$ to a twin-wall enclosure inside which circulates warm water from the storage tank as shown below in Figure 2. 11 [69].




*Source: Yiannopoulos A. C. et al., 2009*

**Figure 2. 11: Schematic of the reactor model configuration with heat transfer processes.**

Yiannopoulos A. C, et al. (2008) developed a mathematical model to predict the temperature distribution within the reactor under steady state conditions and their preliminary results based on model simulations performed with meteorological data from various geographical regions of the world showed that the proposed solar reactor system was promising [69]. The following sections of the model were considered for this work, that is, total heat demand, water storage tank and reactor inlet temperature as described below.

### 2.8.1 Digester energy demand

The total heat demand, $Q_L$, required for a designed solar reactor system is evaluated using Equation (2. 23) below [69].

$$Q_L = Q_r + Q_{Lr} + Q_{Ls} + Q_{Lp} \qquad (2.\ 23)$$

Where:

$Q_r = \pi D L \dot{q}_0$ is heat demand by the reactor content

$Q_{Lr} = (UA)_r(T_m - T_e)$ is the reactor heat losses from the insulated surfaces

$Q_{Ls} = (UA)_s(T_s - T_e')$ is the warm water storage tank heat losses to the surroundings

$Q_{Lp} = (UA)_p(T_s - T_e)$ is the total heat losses from the pipe loop that circulates warm water between the storage tank and the anaerobic reactor.

$(UA)_r$ is the heat transfer coefficient-area product for the anaerobic reactor, $(UA)_s$ is the heat transfer coefficient-area product for the warm water storage tank, $(UA)_p$ is the heat transfer coefficient-area product for the warm water pipe loop, and $T_m$ is the average temperature of the warm water within the twin-wall of the reactor, $T_s$ is the temperature of the water in the storage tank, $T'_e$ is the temperature of the warm water storage tank surroundings, which could be different from the ambient air temperature, $T_e$ if the storage tank is placed indoors [69].

#### 2.8.1.1 Digester heating requirement

The energy required to warm up the digester sludge depends mainly on its specific heat ($c_p$), the temperature difference ($\Delta T$) between ambient ($T_a$) and digester working temperature ($T_d$), and the efficiency of the heating system ($\eta_h$). The necessary heating energy per unit volume (kJ/m$^3$) of the digester can be calculated using either Equation (2. 24) [37]:

$$E_h = \frac{\rho \cdot c_p \cdot \Delta T \cdot F}{\eta_h} \tag{2. 24}$$

In the case of a batch bioreactor, or Equation (2. 25):

$$E_h = \frac{\rho \cdot c_p \cdot \Delta T \cdot F}{\eta_h \cdot HRT} \tag{2. 25}$$

In the case of a continuous bioreactor,

Where:

| | |
|---|---|
| $\rho$ | is density of the fermenting slurry (kg/m$^3$) |
| $c_p$ | is specific heat capacity of fermenting slurry (kJ/kg.$^o$C) |
| $\Delta T = T_d - T_a$ | is temperature difference (K) |
| $\eta_h$ | is the global efficiency of the system to furnish the heat |
| $F$ | is the liquid contained in the reactor (% of reactor volume) |
| $HRT$ | is the hydraulic retention time of the liquid in the bioreactor (days) |

As assumptions, $F$ is usually assumed to be F = 0.9 (90% of reactor volume), the $\rho$ and $c_p$ of water are used for the fermenting slurry in the digester [37].

#### 2.8.1.2 Heat loss

The temperature difference between the digester working temperature $T_d$ and the ambient temperature $T_a$ around the reactor is responsible for the heat loss from the reactor. The lost energy by the digester must be supplied from the digester heating system and it depends on the insulation of the digester from the external environment and the exposed surface. The necessary energy used to replace the heat loss per unit volume of reactor may be calculated using Equation (2. 26) below [37]:

$$E_l = \frac{\left(4.5 \cdot \frac{k}{s} \cdot \Delta t(T_d) \cdot \frac{\Delta T}{D}\right)}{\eta_h} \qquad (2.\ 26)$$

In the case of a batch digester; while the Equation (2. 27) below is used for evaluation in the case of a continuous reactor:

$$E_l = \frac{\left(4.5 \cdot \frac{k}{s} \cdot 24 \cdot \frac{\Delta T}{D}\right) + \left(\rho \cdot c_p \cdot F \cdot \frac{T_d}{HRT}\right)}{\eta_h} \qquad (2.\ 27)$$

Where:

- $E_l$ is rate of heat loss (kJ $h^{-1}$ $m^{-1}$)
- $k$ is the thermal conductivity of the digester walls (kJ $h^{-1}$ $m^{-1}$ $°C^{-1}$)
- $s$ is the thickness of the reactor/insulator walls (m)
- $\Delta t(T_d)$ is the total duration of fermentation (h)
- $T_d$ is the digester temperature
- $D$ is the reactor diameter (m)
- $HRT$ is the hydraulic retention time (h)
- $F$ is the liquid contained in the reactor (%)
- $\eta_h$ is the efficiency of the heating system in the digester
- $s$ is digester insulation walls thickness (m)
- 4.5 is a factor according to the geometrical scale-up criterion that has been adopted

**Thermal insulation**

The total resistance to thermal conduction, that is, the reciprocal of the overall heat transfer coefficient U, accounts for the total insulation of the fermentation slurry in the digester from the outside environment. Total resistance is calculated as the sum of the single resistances, that is, internal fermentation slurry, steel plus insulation and the external air resistances as expresses in Equation (2. 28) where the global thermal resistance $U^{-1}$ is [37]:

$$U^{-1} = {h_i}^{-1} + \frac{s}{k} + {h_e}^{-1} \tag{2. 28}$$

For more than a single insulating material, Equation (2. 29) is used to evaluate the resultant insulation heat transfer coefficient;

$$\frac{s}{k} = \sum_{i=1}^{n} \frac{s_i}{k_i} \tag{2. 29}$$

Where $h_i$ and $h_e$ are the internal and external convective heat transfer coefficients, respectively. For cases where large insulator thickness is used, thus creating higher resistance because of the phenomena of heat transfer in different materials in series, $h_i$ and $h_e$ can be disregarded. Hence, the resistance to heat transfer is considered only in the insulating material [37].

To minimize the amount of heat exchanged between the system and environment, insulation materials play an important role. Insulation material are inhomogeneous solids with very low value of thermal conductivity $k$ because of air enclosed in their pores. Table 2. 10 below shows the thermophysical properties of some materials [37] [71].

**Table 2. 10: Thermophysical properties of some materials**

| **Material** | **Temperature, T** (℃) | **Conductivity, $k$ (W/m K)** | **Density, $\rho$ (kg/m$^3$)** | **Heat Capacity, $c_p$(kJ/kg K)** |
|---|---|---|---|---|
| Steel | 20 | 52 | 7800 | 0.44 |
| Stainless steel AISI 302 | 27 | 15.1 | 8055 | 0.48 |
| Stainless steel AISI 304 | 27 | 14.9 | 7900 | 0.477 |
| Stainless steel AISI 316 | 27 | 13.4 | 8238 | 0.468 |
| Stainless steel AISI 347 | 27 | 14.2 | 7978 | 0.48 |
| Aluminium | 20 | 220 | 2700 | 0.92 |
| Cotton | 30 | 0.04 | 2700 | 1.52 |
| Glass wool | 0 | 0.035 | 100 | 0.65 |
| Expanded polystyrene | 0 | 0.032 | 35 | 0.8 |
| Expanded polyurethane | 0 | 0.021 | 40 | - |
| Cork sheet | 0 | 0.04 | 130 | - |
| Sheep wool | 10 | 0.04 | 28 | - |
| Straw | 20 | 0.058 | 175 | - |
| Recycle paper | 20 | 0.07 | 400 | - |
| Raw clay | 20 | 0.132 | 700 | - |
| Concrete | 15 | 04-0.7 | 2400 | 0.92 |

*Source: Ruggeri B. et al., 2015; Bergman T. L. et al., 2011*

In this study, Stainless steel AISI 316 was considered for the digester and hot water storage tank structural material because of its resistance to rust, good weldability, high mechanical strength, good resistance to stress, corrosion, cracking, and availability in Uganda. Aluminium was not considered because of the high chloride concentration in the warm digesting fermentation sludge though it is cheaper in comparison to stainless steel.

Expanded polystyrene and concrete were chosen as the insulation materials in order to maintain heat losses as minimal as possible because of their low thermal conductivity values and their availability locally in Uganda which excludes importation and additional transportation costs.

### 2.8.1.3 Electrical energy demand

The electrical energy consumption of the digester is for mixing, filling up and emptying the bioreactor using a pump. In batch fermentation, the raw material is pumped in at the beginning of the run and the sludge is pumped out at the end and the reactor is mixed continuously throughout the run. The energy for pumping in the case of a batch reactor can be calculated as the energy necessary to lift the slurry to the top of the reactor by using Equation (2. 30) below [37]:

$$E_P = \frac{\left(q \cdot \rho \cdot W_P \cdot t_r \cdot 9.81 \times 10^{-3}\right)}{V_d} \qquad (2.\ 30)$$

In the case of continuous digester operation, Equation (2. 31) evaluates the energy used for pumping:

$$E_P = \frac{\left(\rho \cdot W_P \cdot 9.81 \times 10^{-3}\right)}{HRT} \qquad (2.\ 31)$$

Given

$$W_P = \frac{\left({}^{g}/_{g_c} \cdot L + {}^{v^2}/_{2g_c} + f_f\right)}{\eta_m} \qquad (2.\ 32)$$

Where:

$W_P$ is the energy to be supplied to the fluid per unit of broth mass, in $kg_f$.m/kg, to transport it from the feed tank to the reactor.

$v^2$ is the velocity of the fluid in the pipe

$L$ is the height of reactor

$g$ is the acceleration due to gravity

$g_c$ is the Newton's-law proportionality factor $g_c$ = 1.2 × $10^8$ (kg m $h^{-2}$ $kg_f^{-1}$)

$q$ is the volumetric flow rate ($m^3$/h)

$t_r$ is the filling time (h)

$9.81 \times 10^{-3}$ is the conversion factor from $kg_f$.m to kJ

$\eta_m$ accounts for the overall efficiency of the pump to convert mechanical energy in energy of motion

$f_f$ represents the energy dispersed as heat generated to overcome the friction force per unit of mass of fluid occurring in the fluid along pipe between the feed tank and the reactor

### 2.8.2 Water storage tank and reactor inlet temperature

The warm water storage tank temperature variation over a change in time of $\Delta t = 1$ hour is estimated using Equation (2. 33) below [69]:

$$T_s^+ = T_s + \frac{\Delta t}{(MC_p)_s}(Q_u - Q_L) \qquad (2.\ 33)$$

Where $T_s$ and $T_s^+$ are the temperatures of the warm water in the storage tank at the beginning and end of the time change $\Delta t$. $Q_u$ is the useful energy gain of the solar collector, $Q_L$ is the total heat demand. $M = \rho V_s$ is the warm water storage tank capacity ($\rho$ is the water density, and $V_s$ is the volume of the storage tank) [69].

#### 2.8.2.1 Vapor pressure

For systems where the water tank is closed with no opening to the atmosphere, the water surface is acted upon by vapor pressure. Vapor pressure is the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phase at a given temperature in a closed system. It indicates the liquid's evaporation rate. Vapor pressure $P_v$ at any given temperature $T$ is expressed as in Equation (2. 34) below [72]:

$$P_v = 2427.9 - 60.726T + 0.44048T^2 \qquad (2.\ 34)$$

Where $P_v$ is in mmHg (1 mmHg ≡ 0.13332239 kPa)

#### 2.8.2.2 Hydrostatic pressure

For fluid tank at equilibrium, every point with in the tank has a pressure exerted on it due to the force of gravity, known as hydrostatic pressure. This pressure increases proportionally with depth measured from the fluid surface due to increasing weight of fluid exerting downward force from above. Hydrostatic pressure $P$ is evaluated using Equation (2. 35) below [71]:

$$P = \rho g h \tag{2. 35}$$

Where:

$\rho$ is density of the fluid

$g$ is acceleration due to gravity

$h$ is depth of the point from the fluid surface

#### 2.8.2.3 Absolute pressure

For closed tank systems, the absolute pressure is the sum of hydrostatic pressure and vapor pressure at a given temperature. Equation (2. 36) below evaluates the Absolute pressure $P_{abs}$ of a system [71]:

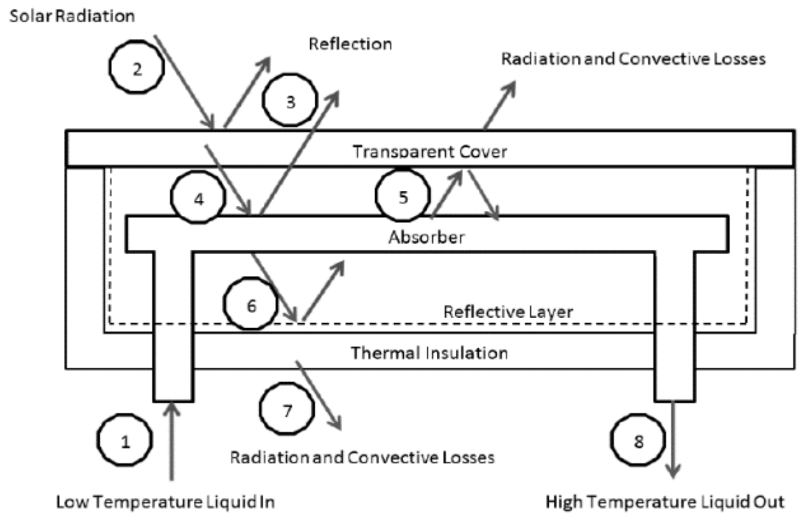
$$P_{abs} = P + P_v \tag{2. 36}$$

Vapor pressure and hydrostatic pressure should be expressed in the same units.

### 2.8.3 Solar collectors

A solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat that is absorbed by a fluid. Collectors use both beam and diffuse solar radiation and do not necessitate any tracking of the sun, and require little maintenance [73].

A solar collector constitutes of the optical part along with the energy conversion path, from solar radiation to thermal, in a solar thermal energy system. Solar collectors are used to convene thermal energy to a liquid medium flowing through the collector in order to use or store the thermal energy elsewhere. A basic solar collector with its components and energy flow paths is shown in Figure 2. 12 below [73].




*Source: Gauche P., 2012*

**Figure 2. 12: Energy flows in a basic solar collector**

The basic solar collector shown in Figure 2. 12 above operates in the following way:

1. working fluid (liquid) enters the solar collector at a low temperature.

2. Solar radiation strikes the collector face.

3. Based on the nature of the cover, a small portion of the incident radiation is reflected. At this point the spectral distribution is still the same and the cover appears transparent.

4. The rest of the incident radiation on the collector is allowed to pass through the cover and strikes the absorber and the electromagnetic radiation is converted into thermal energy, heating the absorber.

5. Due to the elevated temperature of the absorber it now starts to lose heat in the form of thermal radiation and convection. Because of the relatively low temperature of the absorber, the radiation frequencies are substantially lower and at these lower frequencies the cover appears opaque and acts as a radiation shield.

6. The cover now absorbs the radiation which in turn causes the cover temperature to rise. Energy is then lost from the solar collector via radiation and convection losses at the cover.

7. A reflective layer is used to line the interior of the collector to limit losses through the back and sides of the collector. To further reduce the losses, insulation is added to the back and sides of the collector but convective and radiation losses still occur at the outer surfaces.

8. The working fluid (liquid) now exits the solar collector at a raised temperature due to the addition of thermal energy from the absorber.

There are various types of solar collectors available, below are the main types of solar collectors:

- Uncovered absorbers
- Glazed flat plate solar collectors
- Evacuated tube solar collectors

### 2.8.3.1 Uncovered absorbers

Unglazed collectors are often made of black plastic stabilized to withstand ultraviolet light. A great portion of the sun's energy is absorbed since the collector has no glazing. However, because they are not insulated, equally a great portion of the heat absorbed is lost from the collector, especially during windy and not warm conditions on the outside. They can capture heat even during the night when it is hot and windy outside because of their ease of heat transfer to air [74].

Uncovered absorber collectors are best suited for low range temperature applications of less than 30 °C. They are primarily used for outdoor swimming pools, heating seasonal indoor swimming pools, pre-heating water for car washes and heating water used in fish farming operations [74].

### 2.8.3.2 Glazed flat plate solar collectors

They are also known as simple flat plate collectors. The basic parts of this type of solar collectors are: the full-aperture absorber, transparent or translucent cover sheets, and an insulated box. A sheet of high-thermal-conductivity metal with tubes or ducts either integral or attached are usually used as the absorber. To maximize radiant energy absorption and also to minimize radiant emission, the absorber surface is always coated. The cover sheets (glazing) allow sunlight to transmit through to the absorber while insulating the space above the absorber to prohibit cool air from flowing into this space [74].

Flat plate collectors are the widely used type of solar collectors for solar water heating systems in residences and in solar space heating. A flat plate collector is comprised of mainly an insulated metal box with glass or plastic cover (coating) and a dark-colored absorber plate. Solar radiation is absorbed by the absorber plate and transferred to a fluid that circulates through the collector in tubes, for air-based collector systems, the circulating fluid is air and on the other hand, water for the liquid-based collector systems [74].

Flat plate collectors heat circulating fluid to a temperature less than the boiling point of water and they are best options for applications of temperature demands in the range of 30 – 70 °C and for heating requirements during winter seasons [74].

#### 2.8.3.3 Flat plate collectors with Selective coating

For flat plate solar collector absorber plate to maximize the absorption of solar radiation and appropriate conversion to heat, the absorbers should be covered with dark absorbing coating, which is called solar energy absorbing coating. Because the wavelength of solar radiation is mainly concentrated in the range of 0.3 to 2.5 μm, while the thermal radiation absorber plates are mainly concentrated in the wavelength range of 2 ~ 20 μm, to enhance the absorber plate solar radiation absorption capacity, but also reduce heat losses, it requires the use of a selective coating.
Selective coating of the absorber yields a higher absorption rate for shortwave radiation. Selective coating enables collectors to reach absorption rate in the range of 0.93 to 0.95 and emissivity in the range of 0.12 to 0.04, greatly improving the thermal performance [75].

#### 2.8.3.4 Evacuated tube solar collectors

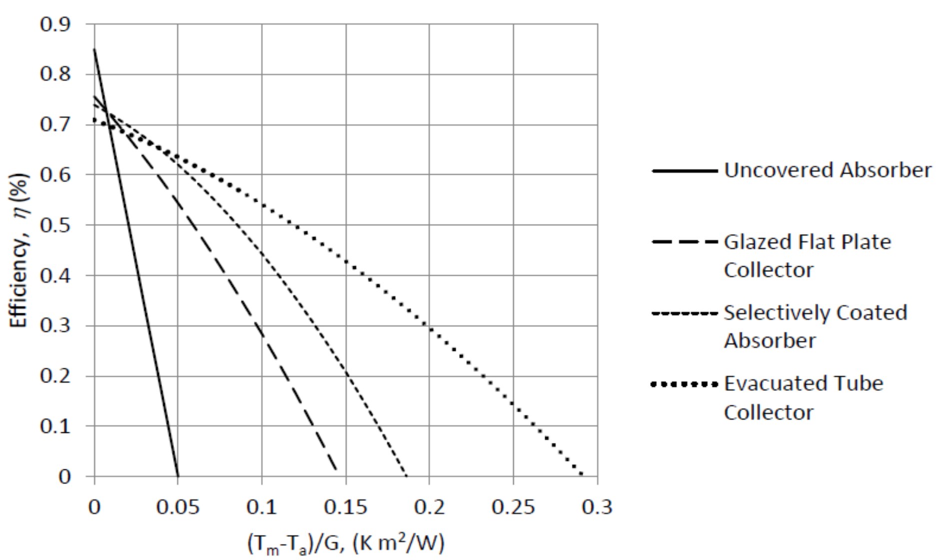
Evacuated (or Vacuum) tubes are solar panel built to minimize convective and heat conduction loss (vacuum is a heat insulator) and they are used when high temperature fluid is required. Different construction types are available [76]:

- Heat pipes or direct flow
- All glass tubes

- With or without concentrator

Glass evacuated tubes are the key component of this type of solar collectors. Each evacuated tube comprises of two glass tubes, and air is evacuated from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss. The outer tube is made of extremely strong transparent borosilicate glass that is able to resist impact from hail up to 25 mm in diameter. The inner tube is also made of borosilicate glass, but coated with a special selective coating, which features excellent solar heat absorption and minimal heat reflection properties. The manifold is heavily insulated with a 2-inch thickness of pre-formed rock wool to keep the heat in. In comparison to flat plates, these heaters are so well insulated that they do not require antifreeze in normal operation [74] [76].

Figure 2. 13 below shows the performance of typical samples of each type of collector [73].




*Source: Gauche P., 2012*

**Figure 2. 13: Typical performance curves for various types of solar collectors**

The efficiency curve is normalized for the solar radiation, G, and the difference between the average collector temperature and the ambient temperature. From the efficiency curve, it can be seen that an uncovered absorber offers the highest maximum efficiency, but also with the lowest maximum outlet temperature. In contrast, an evacuated tube collector has the lowest maximum efficiency but the highest outlet temperature. The flat plate collector with the selective coating offers high outlet temperatures and average efficiency, however, it offers the largest aperture and thus the best output per $m^2$ of installation [73].

### 2.8.4 Types of solar water heater systems

Solar water heater systems are divided into three categories, namely:

- Pumped system
- Integral collector system
- Thermo-Siphoning system

`These categories of solar water heater systems are discussed in detail in the following section below.

#### 2.8.4.1 Pumped system

This system necessitates a pump to pump the working fluid through the solar collectors. It is also divided into two systems, that is direct and indirect pumped systems.

**Direct pumped system**

This system has solar collectors installed on the roof and a storage tank somewhere below. A pump circulates the water from the tank up to the collector and back again. It is called direct or open loop system because the sun's heat is transferred directly to the circulating water through the collector tubing and the storage tank. This system does not require an antifreeze solution or heat exchanger. The system includes differential controller that senses temperature differences between the water leaving the collectors and the colder water in the storage tank. The controller turns on/off the pump based on the temperature of water [54].

**Indirect pumped system**

In this system, an antifreeze solution circulates through the collectors and it necessitates a heat exchanger for heat transfer from the antifreeze to the water in the tank. The antifreeze solution is pumped through a closed loop by a pump. The loop includes an expansion tank, pump and a heat exchanger. The exchanger is coiled in the lower half of the storage tank or around the tank. This keeps the antifreeze from contract with the potable water [54].

#### 2.8.4.2 Integral Collector Systems (ICS)

The ICS is a single unit that combines thermal collection and storage together. They are designed for a simple, durable and inexpensive domestic water heating system. It serves as a preheating solar system to an existing electric or gas water heater. They serve as a good choice for the sunbelt or other mild climates that do not experience hard freeze conditions. It is a passive solar thermal system that does not necessitate the use of pumps, sensors or other mechanical part. It relies on gravity for fluid flow in the system. It has higher piping losses with a central tank [54].

#### 2.8.4.3 Thermo-siphoning system

In the thermo-siphon hot water circulating systems, there is no requirement of a pump, but relies on the principal that hot water rises, a phenomenon known as natural convection. The water in the collector becomes lighter when it is heated and it rises naturally to the tank while cold water in the tank flows down the pipes to the bottom of the collectors, causing circulation throughout the system [54].

Thermo-siphon systems are passive solar hot water heating systems that use flat plate solar collectors. The collectors are usually mounted at a lower elevation than the storage water tank to be heat, allowing free circulation to the collectors. Thermo-siphon systems can circulate potable water or use a heat exchanger and heat transfer fluid [54].

Since the force is only a small difference in density, larger than normal pipe sizes are recommended to minimize pipe friction. At night and moments when the collector is cooler than the water in the tank, the flow in thermo-siphon system reverses, thus cooling the stored water. A prevention mechanism to this would be having the top of the collector well below, about 30 cm below the bottom of the storage tank [77].

Table 2. 11 below shows the comparison of the different types of solar water heater systems [54].

**Table 2. 11:Comparison between the different types of solar water heater systems**

| Specification | Types of solar water heater systems | | |
|---|---|---|---|
| | Pumped | ICS | Thermo-siphoning |
| Cost | Most expensive | Less expensive | Cheap |
| Purpose | Industrial and commercial water heating | District water heating | Domestic small sale water heating |
| Climate conditions | No special environmental conditions | Only warm or sunbelt climate | Special installation conditions needed |
| Efficiency | Most efficient | Less efficient | Least efficient |

*Source: Dennis A. & Burke P. E., 2012*

### 2.8.5 Solar collector design

To maximise energy collected by the solar collector, its energy losses to the surrounding should be minimised by using highly absorbent materials for the collector absorber. Equation (2. 37) below evaluates the useful energy collected by the solar collector [78]:

$$\dot{Q}_{coll} = F_R \left[ (\tau\alpha) - \frac{U_L \Delta T}{G} \right] \quad (2.\,37)$$

Or

$$\dot{Q}_{coll} = \eta_i \cdot A_c \cdot G \quad (2.\,38)$$

Where

$\dot{Q}_{coll}$ Energy collected per unit collector area per unit time

$F_R$ Collector's heat removal factor (defined as the ratio of the heat actually delivered to that delivered if the collector plate were at uniform temperature equal to that of the entering fluid)

$\tau$ Transmittance of the cover

$\alpha$ Shortwave absorptivity of the absorber

$(\tau\alpha)$ Transmittance-absorptance product ($(\tau\alpha) = K_{\tau\alpha}(\tau\alpha)_n$)

$G$ Global incident solar radiation on the collector

$U_L$ Overall heat loss coefficient of the collector

$A_c$ Solar collector receiver area

$\eta_i$ Collector performance efficiency

$\Delta T$ Temperature differential between the average temperature of the collector and the ambient temperature outside the collector.

Test Equations (2. 39) and (2. 40) below are used for evaluating the solar collector efficiency and incident angle modifier $K_{\tau\alpha}$, respectively [79]:

$$\eta_i = \eta_o - a_1 \frac{(T_{av} - T_{amb})}{G} - a_2 \left(\frac{T_{av} - T_{amb}}{G}\right)^2 \qquad (2.\ 39)$$

The incident angle modifier $K_{\tau\alpha}$, is a correction factor defined as the ratio $\tau\alpha$ at some incidence angle $\theta$ to $\tau\alpha$ at normal radiation $(\tau\alpha)_n$, evaluated as follows:

$$K_{\tau\alpha} = 1 - b_o\left(\left(\frac{1}{cos\,\theta_i}\right) - 1\right) - b_1\left(\left(\frac{1}{cos\,\theta_i}\right) - 1\right)^2 \qquad (2.\ 40)$$

Where:

$\eta_i$ is instantaneous efficiency

$\eta_o$ is optical efficiency

$a_1$ $a_2$ & $a'_2$ are constants at a particular wind speed ($a_2 = a'_2 G$)

$G$ is solar radiation

$T_{amb}$ is ambient temperature

$T_{av}$ is average collector temperature

$K_{\tau\alpha}$ is incidence angle modifier

$b_o$ is incidence angle modifier coefficient for first glass cover

$b_1$ is incidence angel modifier coefficient for second glass cover ($b_1 = 0$, for single glass cover)

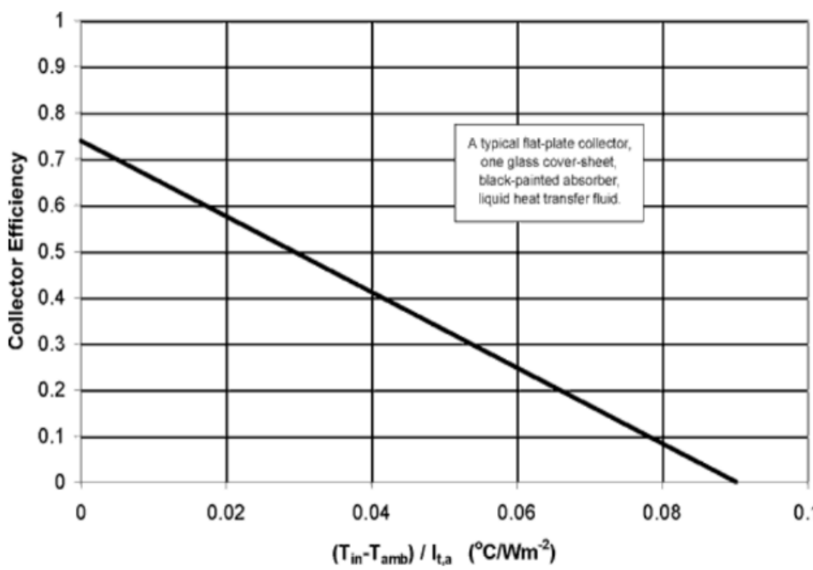
In this study, a glazed flat plate solar collector type was considered based on ease of fabricating them locally as shown in Figure 2. 14 below, being produced in Uganda [80].

*Source: Weiss W., 2014*

**Figure 2. 14: Local production of flat plate solar collectors in Uganda**

The efficiency of a flat plate solar collector can be read off from its performance curve.

Figure 2. 15 below shows the collector performance of a typical collector operating at an ambient temperature of 25℃ [81].




*Source: Struckmann F., 2008*

**Figure 2. 15: Performance curve of a typical flat plate solar collector at 25 ℃**

The performance curve for flat plate collectors vary based on the collector dimensions, insolation, inlet temperature, insulation, radiation incidence and collector tilt angle. The specifications of flat plate collectors are always provided by manufacturers in the products catalogues. Installation details in conjunction with the collector specifications, the performance curve can be generated for the collector for any given location.

#### 2.8.5.1 Pressure drop across a collector

Pressure drop is an important concept in designing of solar collector systems, mainly in sizing of pumps. The pressure drop between the collector inlet and collector outlet is described by quadratic function of the fluid flow rate as shown in Equation (2. 41) below [82]:

$$Pressure\ drop = 8329(Mass\ flow)^2 + 128(MAss\ flow) \qquad (2.\ 41)$$

Equation 2.41 above shows that pressure drop increases with square of the flow rate.

#### 2.8.5.2 Collector tilt

Collector tilt is the inclination of the collector to the sun and the output of a collector system is dependent on this inclination. Flat plate collectors are typically fixed in a tilted position correlating with the latitude of the location which allows for the best capture of the sun by the collectors [83]. For Kiruhura, the case study site for this research, the latitude is 0.1928° S, which is approximately equal to zero degree. However, as a precaution to avoid any objects like leaves and dust from lodging on the collector surface, the collectors were tilted to $15^o$.

### 2.8.6 Working fluid used

Working fluids are not ideal for all applications and for any heating and cooling system, there is need to look out for the fluid with the best properties befitting the system.

Commonly used fluids in solar collectors are;

- Ethylene glycol solution
- Propylene glycol solution
- Water

Ethylene glycol is the mostly used fluid for standard heating and cooling applications. However, it should be avoided if there is any slightest chance of leakage to potable water or food. Also, the dynamic viscosity of ethylene glycol solution increases with temperature consequently resulting in head loss in the piping system [84]. Propylene glycol solution is commonly used instead of ethylene glycol solution to potable water and food contaminations in carries of leakage in the system. Water is commonly used in water heating systems using solar collectors, mainly for swimming pool warming and shower water heating [84].

Table 2. 12 below shows some of the thermodynamic properties of these commonly used fluids [84].

**Table 2. 12: Commonly used working fluids in solar collectors**

| **Fluid** | **Water** | **Ethylene Glycol** | **Propylene Glycol** |
|---|---|---|---|
| Specific heat capacity (J/kg.K) | 4186.8 | ≤ 4186.8 | ≤ 4186.8 |
| Boiling point (℃) | 100 | ≥ 100 | ≥ 100 |
| Freezing point (℃) | 0 | ≤ 0 | ≤ 0 |

*Source: Engineering toolbox, 2014*

## 2.9 System Components

The system is composed of different devices that execute different roles for the success of the system's operation process. In this section, the components used are discussed in brief with emphasis put on their crucial properties that are relevant for this study.

### 2.9.1 Heat exchangers

Are devices in which two moving fluid streams exchange heat without mixing. They are widely utilized in various industries in differing designs.

Double tube also known as tube-and-shell, is the simplest form of heat exchanger, it constitutes of two concentric pipes of different diameters, where one fluid flows in the inner pipe whilst the other in the annular space between the two pipes. Heat transfer occurs across the walls separating the fluids, from the hot fluid to the cold one. The inner tube could make a couple of turns inside the shell in order to increase the heat transfer area, and thus the rate of heat transfer [85].

For the conservation of mass principle for a heat exchanger operating in steady state conditions, it is required that the sum of the inbound mass flow rates equal the sum of the outbound mass flow rates. That is, under steady operation, for each fluid stream flowing through the heat exchanger, its mass flow rate should remain constant [85].

Heat exchangers are characterized with no work interactions ($w = 0$) and negligible kinetic and potential energy changes ($\Delta ke \cong 0, \Delta pe \cong 0$) for each fluid stream. The heat transfer rate associated with heat exchangers depends on how the control volume is selected. The outer shell of the heat exchanger is usually well insulated to prevent any heat loss to the surrounding medium, to only facilitate heat transfer between two fluids within the device [85].

#### 2.9.1.1 Heat exchanged exchanger surface

Properties of each of the fluids in the exchanger can be determined by calculating the film temperature $T_f$ using Equation (2. 42) below [85]:

$$T_f = \left(\frac{T_{in}+T_{out}}{2}\right) \tag{2. 42}$$

Where $T_{in}$ and $T_{out}$ are the inlet and outlet temperatures of the fluid under consideration.

With the value of $T_f$, the properties of the fluid can be read off from the thermodynamics property tables. The properties include thermal conductivity ($\kappa$), dynamic viscosity ($\mu$), kinetic viscosity ($v$), density ($\rho$) and Prandtl number (Pr).

In a heat exchanger, the heat flux or power from fluid 2 to fluid 1 can be determined by using Equation (2. 43) [86]:

$$\dot{Q} = A_{ex} \cdot U.\Delta T_{lm} \tag{2. 43}$$

Where $\Delta T_{lm} = \frac{\Delta T_{in}-\Delta T_{out}}{In\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)}$

The heat transferred to fluid 1 to raise the temperature of fluid 1 is

$$\dot{Q} = A_{ex} \cdot U.\frac{\Delta T_{in}-\Delta T_{out}}{In\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)} \tag{2. 44}$$

The heat gained by fluid 1 can be expressed as [60]:

$$\dot{Q} = C_{pc} \cdot \dot{m} \cdot (T_{out} - T_{in}) \tag{2. 45}$$

From conservation of energy principle, energy gained by fluid 1 equal to energy lost by fluid 2, thus Equation (2 .46) below:

$$C_{pc} \cdot \dot{m} \cdot (T_{out} - T_{in}) = A_{ex} \cdot U.\frac{\Delta T_{in}-\Delta T_{out}}{In\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)} \tag{2. 46}$$

The value of $U$ can be calculated using the formula [86]:

$$U^{-1} = \frac{1}{h} + \frac{b_m}{k_m} \quad (2.\ 47)$$

$$h = \frac{\kappa}{L} Nu \quad (2.\ 48)$$

For flat plate and external flow;

$$Nu = 0.664Re^{0.5}Pr^{1/3} \qquad for\ Re < 5 \times 10^5$$

$$Nu = 0.664Re^{0.5}Pr^{1/3} \qquad for\ 5 \times 10^5 < Re < 10^7$$

$$Re = \frac{VL_c}{v} \quad (2.\ 49)$$

Or $Re = \frac{\rho V L_c}{\mu}$

Where:

$A_{ex}$ is the heat exchanging area (m$^2$)

$C_{pc}$ is specific heat capacity of fluid 1 (KJ/kg.K)

$\dot{m}$ is mass flow rate of fluid 1 (kg/s)

$U$ is the overall heat transfer coefficient including heat transfer coefficients of the fluids and heat conduction through the heat exchanger material

$\Delta T_{lm}$ is the so-called logarithmic mean temperature difference between fluid 1 and fluid 2 for $\Delta T_{in} = T_{in_2} - T_{in_1}$ , $\Delta T_{out} = T_{out_2} - T_{out_1}$

$Re$ is the Reynolds number

$Nu$ is the average Nusselt number

$L_c$ is the characteristic length (m)

$D$ is the tube diameter (m)

$\rho$ is the density of fluid 2 (kg/m$^3$)

$\mu$ is the dynamic viscosity of fluid 2 (m$^2$/s)

$v$ is the kinetic viscosity of fluid 2 (m$^2$/s)

$Pr$ is the Prandtl number of fluid 2

$h$ is the heat transfer coefficient of fluid 2 (W/m$^2$.K)

$b_m$ is the thickness of the heat exchanger material (m)

$k_m$ is the conductivity of the heat exchanger material (W/m$^2$.K)

$\kappa$ is heat conductivity through heat exchanger material (W/m$^2$.K)

#### 2.9.1.2 Energy delivered from warm water storage tank

The rate of energy delivered from the warm water storage tank to the digester through the heat exchanger $\dot{Q}_{col}$, may be expressed in terms of mass flow rate $\dot{m}$ (kg/s) and specific heat of the collector fluid $C_{pc}$(J/kg.K) as shown in Equation (2. 50) below [60]:

$$\dot{Q}_{col} = \dot{m}C_{pc}(T_i - T_o) \tag{2. 50}$$

Where $T_i$ is the temperature of the fluid entering the heat exchanger, identical to the storage tank outlet temperature $T_{co}$, and $T_o$ is the temperature of fluid returning to the storage tank, identical also to the inlet storage tank temperature $T_{ci}$.

Assuming that the manure in the digester is always well mixed and consequently at a uniform temperature, $T$ which varies only with time, the temperature $T_o$ of the fluid returning to the storage tank can be calculated using Equation (2. 51) below [60]:

$$T_o = T_i + (T - T_i)\left(1 - e^{-\left(UA_{ex}/\dot{m}C_{pc}\right)}\right) \tag{2. 51}$$

Where $A_{ex}$ is the exchanger's heat transfer area (m$^2$) and $U$ is the overall heat transfer coefficient (W/m$^2$ $^o$C) [60]. Same expression for $T_o$ above, holds as well for any heat exchanger inserted in the storage tank.

### 2.9.2 Pipe and Duct Flow

Pipes and ducts are of great importance in the transportation of fluids in many engineering applications. Fluid flow through a pipe or a duct usually satisfies the steady-flow conditions and thus, often analyzed as a steady-flow process. This analysis excludes the transient start-up and shut-down periods of the fluid [85].

Under normal operating conditions, there could be a very significant amount of heat gained or lost by the fluid flowing through the pipe or duct, particularly if it is long. In desirable circumstances where heat transfer is necessary, pipes or ducts are designs to foster heat transfer during fluid flow. On other hand, where heat transfer is undesirable, the pipes or ducts are insulated to prevent any heat loss or gain, particularly when the temperature difference between the flowing fluid and the surroundings is large so that heat transfer along the pipe od duct is negligible in this case [85].

In cases where the control volume involves a heating section (electric wires), a fan, or a pump (shaft), the work interactions should be considered. However, fan work is usually small and often neglected in energy analysis. Also, the velocity changes within pipe and duct fluid flow are relatively low, hence, kinetic energy changes being insignificant, more particularly when the pipe or duct diameter is constant and the heating effects are negligible. However, kinetic energy changes could be significant for gas flow in ducts with variable cross-sectional areas especially when the compressibility effects are significant. Likewise, potential energy term could also be significant if the fluid undergoes a considerable elevation change as it flows in a pipe or duct [85].

#### 2.9.2.1 Nusselt number for horizontal cylinder in natural convection

For fluids flowing in pipes having the surrounding with natural convection condition, the Nusselt number is determined using Equation (2. 52) below [71]:

$$Nu = \left[0.6 + \frac{0.387 Ra_D^{1/6}}{\left[1+\left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right]^2 \quad (2.\ 52)$$

For $Ra_D \leq 10^{12}$

Where

$$Ra_D = \frac{g\beta(T_S - T_\infty)D^3}{v^2} Pr \quad (2.\ 53)$$

Where:

$Ra_D$ is Rayleigh number

$\beta$ is volume expansion coefficient

$v$ is kinematic viscosity

$g$ is acceleration due to gravity

$Pr$ is Prandtl number

$T_s$, is cylinder temperature of temperature

$T_\infty$ is ambient temperature of the cylinder

$D$ is diameter of the cylinder

### 2.9.3 Throttling Valves

Ordinary adjustable valves, capillary tubes, and porous plugs are some familiar examples of throttling valves. Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid. Unlike turbines, throttling valves produce a pressure drop without involving any work to the fluid flowing. Because a pressure drop in the fluid is often accompanied by a large drop in temperature, throttling devices are commonly utilized in refrigeration and air-conditioning applications [85].

Throttling valves are usually small devices, with neither sufficient time nor large enough area for any effective heat transfer to take place, the flow through them is assumed to be adiabatic ($q \cong 0$). Also, there is no work done ($w = 0$), and the change in potential energy, if any, is very small ($\Delta pe \cong 0$). Although the exit velocity is often considerably higher than the inlet velocity, in many cases, the change in kinetic energy is insignificant ($\Delta ke \cong 0$) in the fluid. Thus, the conservation of energy equation for this single-stream steady-flow device reduces to $h_2 \cong h_1$ (kJ/kg) That is to say, the enthalpy values at the inlet and exit of a throttling valve are the same, and for this reason, a throttling valve is sometimes called an isenthalpic device. However, it should be noted that for throttling devices with large exposed surface areas such as capillary tubes, heat transfer could be significant [85].

## 2.10 System Economics

Most biogas digester have a lifetime in the range of 25 – 35 years. Over the past years, different economic models for predicting the cost of anaerobic digester system and the cost benefits obtained by using a household biogas digester have been developed. An economic model for assessing the cost-effectiveness of domestic biogas plants is summarized below [87].

### 2.10.1 Net present worth

The net present benefit of the digester system is evaluated by using Equation (2. 54) below [87]:

$$PW = \left(A_g + A_f\right)\sum_{n=1}^{N} W^n - C - \sum_{n=1}^{N} m_n W^n \quad (2.\ 54)$$

Where

| | |
|---|---|
| $PW$ | is the present worth of the incremental net benefit |
| $A_g$ | is the annual incremental benefit from using biogas as cooking fuel |
| $A_f$ | is the annual incremental benefit from using treated slurry as fertilizer |
| $C$ | is the cost of digester |
| $N$ | is the plant lifetime |
| $W$ | is the inflation/interest rate |
| $m_n$ | is the maintenance costs |

### 2.10.2 Levelized cost of energy

The levelized coast of energy makes it possible to compare power plants of different generation and cost structures with each other. Basically, it is the ratio of the sum of all accumulated cost for constructing and operating a plant to the sum of the annual energy generation of the power plant throughout its lifetime. Average LCOE is calculated on the basis of the net present worth method, in which the expenses for investment and the payment streams from earnings and expenditures during the plant's lifetime are calculated based on discounting from a shared reference date [88].

The LCOE of a new plant can be calculated using Equation (2. 55) below [88]:

$$LCOE = \frac{I_o + \sum_{n=1}^{N}\frac{A_n}{(1+r)^n}}{\sum_{n=1}^{N}\frac{M_{n,el}}{(1+r)^n}} \quad (2.\ 55)$$

Where:

| | |
|---|---|
| $LCOE$ | is the Levelized cost of energy (dollar/kWh) |
| $I_o$ | is the investment expenditures (dollars) |
| $A_n$ | is the annual total costs in dollar in year $n$ |
| $M_{n,el}$ | is the produced quantity of energy in the respective year (kWh) |
| $r$ | is the interest rate (%) |
| $N$ | Economic operation lifetime of the plant (years) |
| $n$ | is the year of lifetime (1,2,3…N) |

For anaerobic digester plant intended for only biogas production, the energy content of biogas is evaluated based on the methane content in biogas. If the biogas comprises 60 % methane, the energy content is 6.0 kWh/$m^3$ biogas [89].

IRENA (2012) predicted the LCOE of anaerobic digester plant to fall in the range of 0.06 USD/kWh to 0.15 USD/kWh. The variation mainly caused by the feedstock cost and transportation to the plant [90]. In this study, the feedstock was not priced because it is readily available at every household.

## 2.11 Environmental impact

The utilization of biogas and biomass as an energy source is $CO_2$ neutral because the $CO_2$ released during combustion of the biomass is the same $CO_2$ that the plants assimilated during photosynthesis to create organic matter, the only difference is the rate at which $CO_2$ is being reintroduced to the atmosphere. Burning of biomass is simply $CO_2$ recycling into the biosphere [4].

Biogas utilization helps to reduce the greenhouse gases emissions based on the magnitude of the fuel being replaced. If biogas is used instead of firewood, there will be no reduction in $CO_2$ emissions, because the use of firewood is already $CO_2$ neutral, but only the amount reintroduced per time differs. If, however, biogas replaces fuels like diesel and gasoline, then less oil will be used and thus a reduction in emissions [4].

It is estimated that the digestion of animal manure in a biogas plant reduces the emission of greenhouse gases by approximately 0.3 and 0.6 kg $CO_{2eq.}$ per kg organic matter (volatile solids) for pig and cattle slurry, respectively [4]. From these values, the amount of $CO_2$ emission avoided by digesting the animal slurry in a digester can be estimated for respective feedstock.

Household digester could result in deduction in environmental pressure by reducing forest degradation/deforestation and GHG emissions. A study by Garfi M. et al. (2011) in Peruvian Andes showed that substituting firewood with biogas to cover about 60 % of the cooking requirements resulted in a decrease of firewood consumption by 50 – 60 % and cooking time by 1 h [91].

### 2.11.1 GHG emission reduction

Firewood is the main source of GHG emissions in rural communities, thus, substituting it with biogas can lead to amass GHG emission reduction.

The emissions of a given GHG by the type of fuel substitute with biogas is given by Equation (2. 56) below [91]:

$$ERES = FS_{fuel} \cdot EF_{GHG;fuel} \quad (2.\ 56)$$

Where:

| | |
|---|---|
| $ERES$ | is the emission of a given GHG by the fuel substituted by biogas ($tonnes$) |
| $FS_{fuel}$ | is the amount of fuel substituted with biogas ($tonnes$) |
| $EF_{GHG;fuel}$ | is the emission factor of a given GHG by the fuel ($kg \cdot ton^{-1}$) |

For the case of firewood, the following emission factor values are considered, given in the Emission Factors for Greenhouse Gas Inventories [92].

- $CO_2$ $EF_{CO_2;wood} = 1640\ kg_{CO_{2eq.}} \cdot ton_{wood}{}^{-1}$,
- $CH_4$ $EF_{CH_4;wood} = 3.15\ kg_{CO_{2eq.}} \cdot ton_{wood}{}^{-1}$ and,
- $N_2O$ $EF_{N_2O;wood} = 18.774\ kg_{CO_{2eq.}} \cdot ton_{wood}{}^{-1}$

In this study, it was considered that biogas was to substitute 75 % of firewood usage by the households.

And GHG emission reduction due to the manure digestion, as opposed to storage is given by Equation (2. 57) below [91] [92]:

$$ERMM = EF_T \cdot N_T \quad (2.\ 57)$$

Where

| | |
|---|---|
| $ERMM$ | is the GHG emissions reduction due to the manure digestion in the open, as opposed to storage ($kg_{CH_4} year^{-1}$) |
| $EF_T$ | is the emission factor for the defined animal population ($kg_{CH_4} head^{-1} year^{-1}$) |

$N_T$ is the number of heads of livestock species T per household with digester

$T$ is the category of animal

In this study, $ERMM$ was determined from $CH_4$ emission, and the animal category is cow. Each family is considered to have 7 cows ($N_T = 7$) which only stay in the confinement overnight.

The emission factor in this case for the African region is $EF_{cow} = 31\ kg_{CH_4} head^{-1} year^{-1}$ [93]. The $CO_{2eq.}$ of methane emission is $25 \times 31\ kg_{CH_4}$ [2].

$$EF_{cow} = 775\ kg_{CO_{2eq}} head^{-1} year^{-1}$$

The emission of GHG due to biogas consumption ($EBC$) is evaluated using Equation (2. 58) below [91]:

$$EBC = BC \cdot EF_{GHG;biogas} \qquad (2.\ 58)$$

Where

$EBC$ is the emission due to biogas consumption

$BC$ is the biogas consumption ($tonnes$)

$EF_{GHG;biogas}$ is the GHG emission factor for biogas combustion

Emission factor was considered as follows for the respective GHG gases [92]:

- $CO_2$ $EF_{CO_2;biogas} = 0.025254\ kg_{CO_{2eq.}} \cdot ton_{biogas}{}^{-1}$,
- $CH_4$ $EF_{CH_4;biogas} = 3.88 \times 10^{-5}\ kg_{CO_{2eq.}} \cdot ton_{biogas}{}^{-1}$
- $N_2O$ $EF_{N_2O;biogas} = 9.1188 \times 10^{-5}\ kg_{CO_{2eq.}} \cdot ton_{biogas}{}^{-1}$

The amount of biogas consumption in this study was estimated as $1.0\ m^3\ day^{-1}$ for 75 % of all cooking energy demands by a household considering that a family cooks breakfast, lunch and supper every day.

The total emission reduction (NET) expressed in $kg_{CO_{2eq}}$ is estimated by Equation (2. 59) below [91]:

$$NET = ERES + ERMM - EBC \qquad (2.\ 59)$$

Agea J. G. et al. (2010), in their study on household firewood consumption and its dynamics in Kalisizo Sub-county, central Uganda, they found out that on average, a household with a family size of about seven (7) persons consumes $1.56\ m^3$ of firewood per year and spending about 100 USD per year on firewood [94]. Some of the commonly preferred firewood species include *Sesbania sesban, Eucaluptus, Calliandra calothyrsus, Ricinus communis, Ficus natalensis and Mangifera indica* [94].

Since all the above mentioned firewood species have different densities, in this study a density of $1121\ \mathrm{kg/m^3}$ corresponding to *Eucalyptus microcarpa* (Grey box) [95], was used for evaluation of firewood mass used per household.

# Chapter 3. CASE STUDY

**Outline:**

## 3.0 Introduction

Due to financial constraint, there was no possibility of visiting any anaerobic digester plant in Uganda nor the intended case study site, Kiruhura in Uganda. Alternative measures were undertaken in order to have practical knowledge of the anaerobic digester plant operation in real life state.

Two biogas plants were visited in this study; one operating in thermophilic conditions situated in Bavaria, Germany and another one in psychrophilic conditions situated at the university of Cape Town, South Africa. The following sections 3.1 and 3.2 below discuss in detail the operation of these plants.

Section 3.3 discusses the experimental data of an anaerobic digester operating in mesophilic conditions for laboratory experiments carried out by Prakash Thapa in Norway. The experimental data was compared with the anaerobic digester model developed in this study to evaluate its agreement with real life operational systems.

## 3.1 WGV Biogas Plant

Courtesy of German ministry of Higher Education and Research (BMBF), during the Science Slam Winner Team visit to Germany, WGV[1] biogas plant was visited and used as a case study for the thermophilic operating anaerobic digester systems. This section discusses the details of WGV biogas plant.

WGV biogas plant is situated at WGV recycling GmbH Quarzbichl 12, 82547 Eurasburg in Bavaria, Germany. WGV recycling is a dumping center of all kinds of waste and at this location a biogas plant was constructed in 2014 to utilize the deposited organic waste for biogas production. The plant is a public private owned investment run with no profit oriented ambitions but to provide electricity by utilizing the available organic waste in the community to produce biogas that is later converted to electricity which is fed into the state grid line.

[1] WGV Wertstoffgewinnungs- und Vermarktungsgesellschaft

The biogas plant handles 25, 000 tonnes of waste per year gathered from the surrounding communities. The community pays to the plant administration to deposit their waste at its premises for recycling. Figure 3. 1 below shows waste storage area of the plant.

**Figure 3. 1: Waste storage area**

As shown in figure 3. 1 above, the organic waste contains some inorganic materials. The waste is sorted prior to feeding it into the digester to remove plastics, synthetic and metallic materials that could have come along with the organic waste, these materials are shown in Figure 3. 2 below, sorting out of such materials is done using a machine. The sorted organic waste is chopped to 60 mm size using a machine shown in Figure 3. 3 below to increase the reaction surface area of the fermentation slurry. The feed is introduced into the digester at an interval of 15 minutes with a whole sum daily feed of 70 tonnes. There are no tests carried out on the influent to establish its total solid and volatile solid contents prior to feeding it into the digester. The influent is diluted before introduction to the digester to 60 % water for easy of pumping and flow in the system.

**Figure 3. 2: Sorting residues from the waste**

**Figure 3. 3: Waste chopping machine**

The plant deploys a dry digester system, that is digests slurry with high solids concentration. The digester has a volumetric capacity of 1, 600 m$^3$ with a structural composition of 30 cm thick stainless steel and 20 cm thick concrete shown in Figure 3. 4 below. The fermentation slurry has a retention time of 20 days in the digester before being egested. The fermentation slurry is maintained at a uniform circulation using low speed electric driven impeller system as shown in Figure 3. 5 below that run all the time with a backup generator.

**Figure 3. 4: Anaerobic digester**

**Figure 3. 5: Slurry mixing system**

The digester operating temperature is maintained at 50 ℃ (thermophilic conditions) by using part of the produced biogas to heat the digester. These conditions foster short retention time for the fermentation slurry in the digester and increased biogas production by the digester. The digester produces 70 to 80 $m^3$ of biogas per day.

The effluent at the end of 20 days is always about 75 – 80 % water, shown in Figure 3. 6 below. The water is drained from the effluent for reuse while the solid effluent is stored for 14 days before it is decomposed. The gases from the solid effluent are tested to ensure it meets the environmental standards. Otherwise, it is treated with ammonia to purify the gases and a bio-filter is used to tap off toxic gases. The decomposed solid material is chopped to 8 mm size before it is availed to the farmers to buy and use as fertilizer in their gardens as shown in Figure 3. 7 below. The extracted liquid content can also be availed to farmers on request, it is stored for a long period in a large dome shaped tank shown in Figure 3. 8 below.

**Figure 3. 6: Digester effluent**

**Figure 3. 7: Decomposed solid digestate**

**Figure 3. 8: Liquid effluent storage tank**

The produced biogas is used for electricity generation in the generator box shown in Figure 3. 9 below. The generator has a peak power of 800 kWp electricity and on average, the plant produces 650 kW of electricity which is fed into the grid system. The plant produces on average $5.7 \times 10^6$ kWh per year and in 2015, it produced $5.1 \times 10^6$ kWh. The plant also produces $6.0 \times 10^6$ kWh of heat of which 60 % is used for digester heating and for other heating requirements at the plant while 40 % is wasted.

**Figure 3. 9: Electricity generator box**

The produced electricity is sold to the state grid at a feed-in tariff of 15 cent Euro per kWh. The buying price from the state grid is 10 cent Euro per kWh.

Unlike this study designed digester system, WGV biogas plant only uses green and organic waste and not animal waste as feedstock. It is also a large scale plant when compared to the intended study plant which is a small scale biogas plant using animal manure, cattle manure mainly.

In comparison to the study aim, the digester is to be heated using solar heating system rather than diverting part of the produced biogas to heat the digester. In this study, the digester effluent will not be separated and no possibility of recycling of the sludge.

This plant uses a dry digester system while in the study, a wet digester system is used. That is, the influent is diluted to averagely 8% total solid content. Unlike in this plant where impeller system is used to mix the slurry, gas mixing method is used in the study because it offers high mixing efficiency.

## 3.2 University of Cape Town Biogas Plant

With the assistance of Professor Harro von Blottintz at University of Cape town in conjunction with my supervisor, Professor A. Ben Sebitosi, it was possible as well to visit and study the operation of this biogas plant at the university of Cape Town, South Africa. This plant operates at psychrophilic temperatures. This section gives details on how this plant operates.

Early 2011, a household scale underground anaerobic digester of 6 $m^3$ capacity was installed at the Leo Marquard Hall residence of the University of Cape Town. The pre-fabricated anaerobic digester supplied by AGAMA Energy works at the ambient temperature, averagely 16 ℃ with no heating system incorporated. The digester has a daily fresh solid feedstock of 35 kg, a collection of organic kitchen and canteen wastes.

The digester has 4.05 $m^3$ reactor volume, 0.95 $m^3$ gas storage volume and an expansion volume of 1.0 $m^3$. The digester has dimensions of 2.16 m diameter and 2.225 m height with a thickness of 0.011 m designed to operate in temperature ranges of 10 to 40 ℃. The digester is fed in a 1:1 ratio of fresh feedstock to water. The digester has an ideal biogas rate of 3.8 $m^3$ per day based on the feedstock used.

Figure 3. 10 below, shows a typical pre-fabricated anaerobic digester supplied by AGAMA Energy the kind that was installed at the university of Cape Town [96].

*Source: Agama Biogas, 2010*

**Figure 3. 10: Pre-Fabricated Anaerobic Digester by Agama Biogas (Pty) Ltd**

At the initialization of the anaerobic digester, it was inoculated with cow manure before being fed with kitchen waste, canteen waste and dining hall scrapings. The gas produced by the digester is transported via pipeline back to the kitchen to supplement the cooking energy requirements via an additional biogas stove. Daily burning times of up to an hour on a 4.5 kW biogas stove have been achievable at times. Thus, on average yielding 4.5 kWh on a daily basis for cooking.

Though kitchen wastes have notably high methane production potential in comparison to livestock waste, the digester's gas production rate is low which is a characteristic of psychrophilic operating digesters. The effluent is directly channelled to the sewerage treatment system though there are future plans of utilising it for other purposes.

Since the digester operation mainly relies on students' presence in the university, its productivity retaliates over the semester breaks. Because the digester is used as means of waste management, there is no pressing drive to improve its gas production rate by either heating or increasing its daily influent supply. Furthermore, there are no gas tests carried out of the biogas constituents to determine their percentage contribution to biogas.

In comparison to the average ambient temperature of this study's case study site, the AGAMA digester system would be operating at relatively uniform temperature throughout the year, given that it would be operating in the tropics, unlike the case at the University of Cape Town where it is affected by changes in weather seasons throughout the year.

## 3.3 Experimental Anaerobic Digester Setup and Data

The experimental data sets used in this study to validate this study anaerobic digester model were obtained from the study carried out in 2012 by Prakash Thapa entitled ‘Anaerobic Conversion of Glycol Rich Industrial Wastewater to Biogas’ at the University of Stavanger, Norway [97]. Below is the brief description of the substrate solutions used in his study that were also considered for the study model.

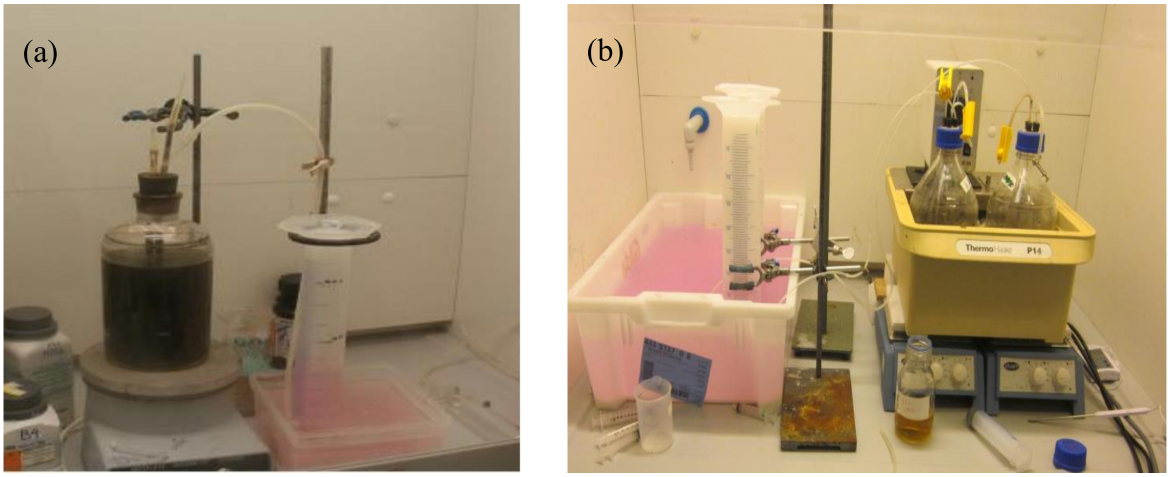
One litre glass flasks were used as reactors which were initially fed to capacity with sewage sludge as the substrate and the sludge was gradually replaced by a substrate solution day by day of 100 ml for the respective experiment setup. The sludge had a hydraulic retention time of 10 days and the data was recorded for a period of 39 days. The substrate solutions used in the experiments were prepared as described below using yeast extract manufactured by Merck, Germany [97].

The granulated yeast solution used in the experiments was prepared using 6.66 grams of granulate yeast extract in 200 ml solution of tap water which is an equivalent of 33.3 g/l and the pH of the solution was found to be neutral. The solution had the following characteristic [97]:

- COD of the solution = 30.67 g COD/L
- Total solid content = 0.94 g TS/g yeast
- Total Volatile Solids content = 0.795 g TVS/g yeast

The solution used in Experiment 1 was prepared and kept for 2 days while the solution used in Experiment 2 was freshly prepared and used then. Experiment 1 operated in the temperature range of 23 ℃ to 40 ℃ with an average temperature of 34.8 ℃ while Experiment 2 operated in the temperature range of 33.3 ℃ to 37.8 ℃ with an average temperature of 35.4 ℃ [97].

Figure 3. 11 below shows the experimental set of the Experiment 1 and Experiment 2 conducted by Prakash [97].




*Source: Prakash T., 2012*

**Figure 3. 11: Experimental Setup of anaerobic digester systems used by Prakash: (a) - Experiment 1 setup and (b) – Experiment 2 setup**

In Experiment 1, the reactor was placed on a hot plate magnetic stirrer with heat and speed control, it was operated in mesophilic conditions that is, average temperature of 34.8 °C was maintained throughout the experiment [97].

In Experiment 2, the reactor was submerged in a water bath, the temperature of the water bath was maintained constant at about 38 °C. The water bath was itself placed above two hot plate magnetic stirrers directly and positioned in such a way that each reactor in the water bath reclined just above the plates for stirring purposes [97].

Gas collector tube was connected to an inverted volumetric cylinder filled with 0.1 M $Ca(OH)_2$ solution and dipped in a container for gas collection. The container contained 0.1 M $Ca(OH)_2$ solution for $CO_2$ absorption which acted as a barrier solution. Furthermore, phenolphthalein solution was added in the barrier solution and it imparts the pink color in alkaline solutions where the change in color indicates whether $Ca(OH)_2$ is available to absorb $CO_2$ or not [97].

The substrate solution described above was used in this study anaerobic digester model at the respective experiment temperatures to determine the respective coefficients of determination against the laboratory experimental results obtained by Prakash.

# Chapter 4. METHODOLOGY

**Outline:**

## 4.0 Introduction

In order to achieve the aim and the major objectives of this research, the research was carried out using the following approaches detailed below. The research method was divided into distinct steps: sizing and simulation of the individual components of the system, and harmonizing of the components into an integrated wholesome system with its simulation and calculations.

## 4.1 Software Review

This section gives a brief description of the software tools that were used in this research giving highlights of the computational approach for the research.

### 4.1.1 Engineering Equation Solver (EES) Software

EES is an acronym for Engineering Equation Solver software developed for Microsoft Windows Operating System. The basic function provided by EES is the numerical solution of a set of algebraic equations. Equally, EES solves differential and equations with complex variables, does optimization, provide uncertainty analyses, linear and non-linear regression, convert units and check unit consistency and generate publication-quality plots [98].

EES simplifies the process for the user by automatically identifying and grouping equations which must be solved simultaneously. It also provides built-in mathematical, thermophysical property functions, most organic refrigerants (including some of the new blends), air tables, transport properties for most substances, psychometric functions and JANAF thermochemical table data for many common gases that are useful for engineering calculations [98].

EES allows the user to enter his or her own functional relationships in three ways:

- First, a facility for entering and interpolating tabular data is provided from which tabular data can be directly used in the solution of the equation set.
- Second, EES language supports user-written functions and procedure similar to those in Pascal and FORTRAN. It also provides support for user-written modules, which are self-procedures, and modules can be saved as library files which are automatically read in EES when it is started.

- Third, compiled functions and procedures, written in a high-level language such as Pascal, C or FORTRAN, can be dynamically-linked into EES using the dynamic link library capability incorporate into the Windows operating system.

With these three methods of adding functional relationships, EES has very powerful extended capabilities as a programming language [98].

EES is useful in design problems in which effects of one or more parameters need to be determined, providing capabilities with its parametric table that is similar to a spreadsheet. The user identifies the independent variables and EES calculates the dependent variables in the table. The variable relationships can be displayed in publication-quality plots of EES. EES also provides capability to propagate experimental data uncertainties to provide uncertainty estimate of calculated variables [98].

### 4.1.2 System Advisor Model (SAM) software

System Advisor Model (SAM) software is an open source software developed in 2005 by the National Renewable Energy Laboratory (NREL) with the support of the U.S. Department of Energy. SAM uses SAM Simulation Core (SSC) library a package of tools by the Software Development Kit (SDK) to create renewable energy system and project models. The SDK allows for the use of modules from SSC library in Windows, OS X, or Linux applications that are written in C++, C#, MATLAB, or Python. SAM also makes it possible to work with external models developed in EXCEL or the TRNSYS simulation platform [99].

SAM’s scripting language SamUL allows for user-written programs within the SAM user interface to control simulations, change values of input variables and write data to text files.

System Advisor Model (SAM) software is a performance and financial software designed to facilitate decision making in the renewable energy field. SAM is an electric power generation model and assumes that the renewable energy system delivers power either to an electric grid, or to a grid-connected building or facility to meet electric load. It does not model thermal energy systems that meet a thermal process load. SAM also does not model isolated or off-grid power systems, and does not model systems with electricity storage batteries [99].

It is a user's responsibility as an analyst to review and modify all of the input data as appropriate for each analysis. If the input variable values are satisfying, the user can run the simulations, and then examine results. A typical analysis involves running simulations, examining results, revising inputs, and repeating that process until reliable results are obtained [99].

System advisor model requires weather data of the selected location, financial regulation and project technical specifications as inputs. The software runs using weather data in form of TMY2, TMY3 or EPW files containing the different weather conditions of the site including (temperatures, wind speed, solar irradiation etc.). Technical performances are generated using hourly weather data, therefore hourly energy output is estimated and then yearly performances of the system and its components are calculated resulting in the total annual output. The software offers many financial and economical types of analysis for energy projects using as inputs to the analysis period equivalent to the system lifetime, discount rate, inflation rate, loan amount and loan rate [100].

SAM software can be downloaded from the website with a request of registration for an account on the website. SAM's website includes software descriptions, links to publications about SAM and other sources [99].

### 4.1.3 Meteonorm Weather data

Meteonorm is a meteorological database containing climatological data for solar engineering applications at every location on the globe. The data is stochastically generated typical years from interpolated long term monthly means and they represent an average year of the selected climatological time period based on the user's settings. Meteonorm is a standardization tool permitting developers and users of engineering design programs access to a comprehensive, uniform meteorological data basis [101]. The used software is developed by Meteotest institute, it uses both ground stations and satellites images weather measurements. For the locations where there are no weather measurements stations, the software uses results that are interpolated between locations where data is available [101].

The meteonorm radiation database is based on 20 years' measurement period, the other meteorological parameters mainly on 1961 and 2000-2009 means. Comparisons with longer term measurements show that the discrepancy in average total radiation due to choice of time period is less than 2 – 3 % root mean square error for all weather stations [101]. In general, the hourly model tends to slightly overestimate the total radiation on inclined surfaces by 0 – 3 % depending on the model and the discrepancy compared to measure values is $\pm$ 10 % for individual months and $\pm$ 6 % for yearly sums [101] [102].

#### 4.1.3.1 Kiruhura Meteonorm data

In this study, the meteonorm weather data file for Kiruhura was generated with the following uncertainty of yearly values:

- Global irradiation Gh =5 %
- Beam irradiation Bn = 9 %
- Ambient temperature Ta = 2.4 %
- Variability of Gh/year = 3.7 %

The radiation of Kiruhura was generated by meteonorm by radiation interpolation of locations: Mbarara (50 km), Kasese (89 km), Entebbe (203 km), Kampala/Kibera (209 km) and Namulonge (217 km) with 36 % share of satellite data. The site temperature was obtained by temperature interpolation of locations: Kisumu (439 km), Nakuru (589 km), Eldoret (504 km), Meru (761 km), Nairobi/Jomo Kenyatta (691 km) and Garissa (982 km). Some of the meteonorm data for selected days of the year of Kiruhura are shown in Appendix C-1.1 and the annual average weather data in Appendix C-2.1.

The TMY3 data file generated from meteonorm gives hourly meteorological data values of weather conditions at the site running from 1 to 8760 data points corresponding to 00:00 Am of 1$^{st}$ January to 11:00 Pm of 31$^{st}$ December mounting to 1-year[2] period represented in hours. Thus, in this site, days and day hours were represented by their respective hours in the years for consistence with the data format used in the simulation of the designed system. It should be noted that the TMY3 had not include data values for 29$^{th}$ of February.

[2] 1-year ≡ 8760 hours

## 4.2 System Layout

Figures 4. 1 shows the layout diagram of the solar-aided anaerobic digester system that was designed in this study. The design was adopted to evaluate the yield of biogas at thermopphilic digester temperature and anaerobic conditions favorable for microorganism activities in the system at the selected site.

### 4.2.1 System layout diagram

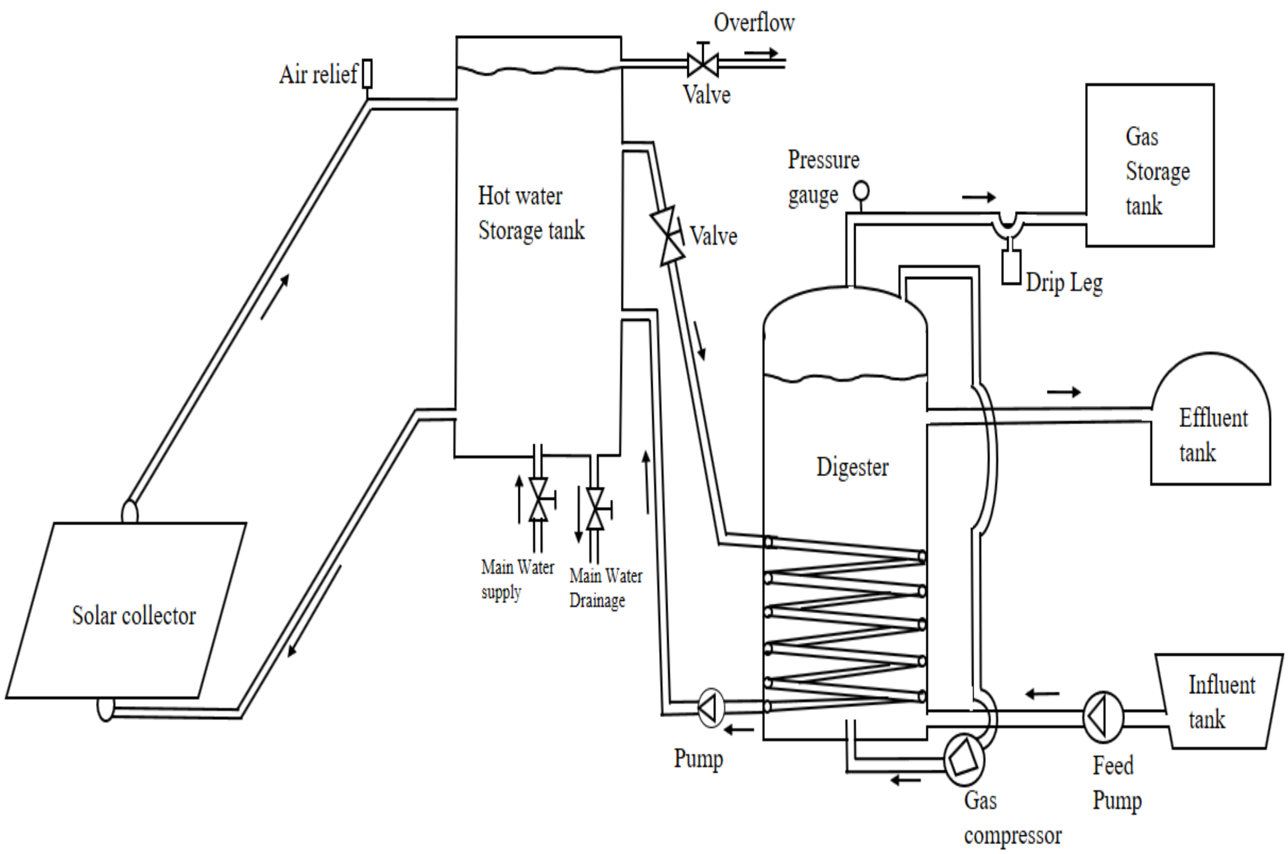



**Figure 4. 12: Designed system layout diagram of the study**

For effective operation of the designed system shown in Figures 4. 1 above, it was crucial to size every component of the system to operate at its optimal and most efficient point. Section 4.3 to 4.5 detail the sizing steps taken in this study to optimize the operation of the designed system for effective results. Secondary treatment of the effluent, biogas purification and feedstock transportation to the plant are not discussed in this study.

## 4.3 Solar-aided Anaerobic Digester System

This system constitutes of mainly two components: anaerobic digester and the solar heating system. Each of these will be described individually in this section and also as a whole assembly with their different parameters of emphasis in the research and simulations.

### 4.3.1 Anaerobic digester

Anaerobic systems can be unstable mainly because of feed overload or presence of an inhibitor or inadequate temperature control. This section details the design and sizing of the anaerobic digester used in this study.

Biomass feedstock, mainly cattle manure was utilized as feedstock to optimize the biogas yield of the digester and to optimize the digester temperature. The digester can however, be fed with any other organic material.

In this research, a continuous stirred tank reactor (CSTR) was considered as the system digester using the gas mixing method as the fermentation slurry mixing approach for the design. The produced gas is injected into the fermentation slurry to mix it using a gas compressor.

A small scale digester of volume 2.00 $m^3$ was designed to be fed by cattle manure as its feedstock. From literature, it is noted that each household on average has seven (7) cattle which on average each produces 14 kg per day. In this research, it was estimated that a household can only collect 65 % of manure slurry produced by each cattle, that is in the confinement and the other 35 % is lost in the cattle grazing field. Thus, a sum of about 63.7 kg per day of cattle manure available as feedstock for the digester. The cattle manure was estimated to constitute 12 % TS and volatile solids (VS) of 85 % of TS for every kilogram of cattle manure. The digester was sized based on the general cylindrical volumetric assumptions given in the literature.

The daily influent addition to the digester was sized taking into consideration that kinetic parameter $K$ should not exceed 1.64 for the digester to operate efficiently at the optimum possible temperature and with ease since excess of stock in the digester may result in digester inhibition and failure.

For ease of pumping the fermentation slurry influent, the influent was diluted to 8 % from 12% total solid content in a 2:1 ratio of cattle manure to water. The ratio was derived using the dilution expression stated in literature.

The digester system was designed to operate in thermophile temperature range and this was to be achieved by use of an external heating system based on solar to ensure that there is no digester temperature variation of close to 1 ℃ in a single hour with the average operating temperature of 50 ℃.

A user defined model was written in EES software to optimize the operation of the digester. The user-written model was used to assess the effect of variation in cattle manure supplied per day, hydraulic retention time and digester temperature have on the methane production rate and cumulative methane yield from the digester. The results were recorded and the relationships discussed in detailed in chapter 5.

#### 4.3.1.1 Accessory tanks

Gas storage, Effluent and influent tanks were sized as a result of the designed digester and its optimal daily feedstock. The influent (mixing) tank was sized to a capacity of 125 % of the daily influent and the effluent tank to a capacity of 5 times the daily influent. Gas collector tank was sized to a capacity of twice the daily gas production.

### 4.3.2 Solar heating system

For the optimization of the anaerobic processes in the digester, heating is necessary and this additional heat required by the digester was be generated by the solar heating system. A solar heating system was designed befitting the heating needs of the anaerobic digester designed as described above. The system constitutes of a hot water storage tank and solar collector system with respective pumps and fluid delivery tubes.

#### 4.3.2.1 Digester heating system

The digester was designed with an inner copper tube coiling used as the heat exchanger between the circulating hot water in the tube and the digester fermentation slurry. A copper tube of 0.018 m and 0.02 m inner and outer diameters, respectively was used. The copper coil was designed in such a way that the outlet water is at least 50 ℃ or above for already stabilized digester operating at a minimum of 50 ℃. The copper tube length was determined based on the digester diameter.

The system was designed in such a way that hot water flowing to the digester heating system flows at a constant flow rate in order to avoid extreme temperature changes caused by fluctuations in the water flow rate. The flow rate used to determine the copper tube length was considered as the flow rate for the designed system since the flow as well was used to determine the size of the hot water storage tank required for heating the digester.

#### 4.3.2.2 Hot water storage tank

The hot water storage tank was designed to store hot water at an average of 51 ℃ maintaining the digester temperature at an average of 50 ℃ with a consideration that the site has an average of 6 hours of sunshine everyday throughout the year as noted in the literature. The tank was designed to ensure that mass flow of hot to the coil in the digester can take at most 2 hours for the digester operating temperature to raise by 1 ℃. The tank was designed in such a way that the water occupied 95 % of its volume and the 5 % left for pressure balance and water expansion in the tank.

The storage tank was designed with dimensions of height to diameter ratio of 8:5 respectively, in order to maximize the pressure head of water in the tank. Same structural and insulation dimensions were used as those used for the digester tank in order to minimize the heat losses to the surround. The storage tank was sized with a 20 % allowance of water volume.

A model was written in EES software to size and optimize the hot water storage tank so as to meet the heat requirements of the digester. The code was run for various mass flow rates in order to determine the best rate for sustaining the digester conditions and at a minimum of temperature increment of less than 1 ℃ per hour from 21 ℃ to 50 ℃.

#### 4.3.2.3 Solar collector system

Solar collector system was designed with constraint that it should be able to heat up the water tank temperature of 60 ℃ on average. Glazed flat plate collectors were considered for this study because of their ease of being fabricated locally.

The mass flow to the collector system was determined by considering a flow that would result in heating the water in the storage tank from 21 ℃ to 60 ℃ in at least 5 hours during a sunny day.

The attained mass flow of water to the collectors was use in System Advisor Model (SAM) software to simulate the solar collector system. Alternative Energy (AE-26) glazed flat plate collector of area 2.35 $m^2$, Incidence Angle Modifier (IAM) of 0.19 and nominal efficiency ($\eta_0$) of 0.691 was used in the simulation. The collector system was simulated at tilt angle of 15 ° and 0 ° azimuth angle. The software was fed with the scaling parameters of the required hot water storage tank that were obtained as detailed in section 4.3.2.2 above. The details used in the program were extracted from the flat plate catalogue. The Alternative Energy (AE-26) collector has a dependable lifespan of 30 years, upon which the study designed system lifespan of 30 years was based. Details of Alternative Energy (AE-26) glazed flat plate collector are shown in Appendix A-1.1 of this report.

From the generated weather data for Kiruhura, location: 0.1928° S, 30.8039° E from meteonorm, a number of important parameters were studied in comparison to the literature finding in order to draw an explicit conclusion of the values to use for different parameters in the simulation.

Figure 4. 2 below, shows the hourly irradiance-incident (W/m$^2$) for the data used.

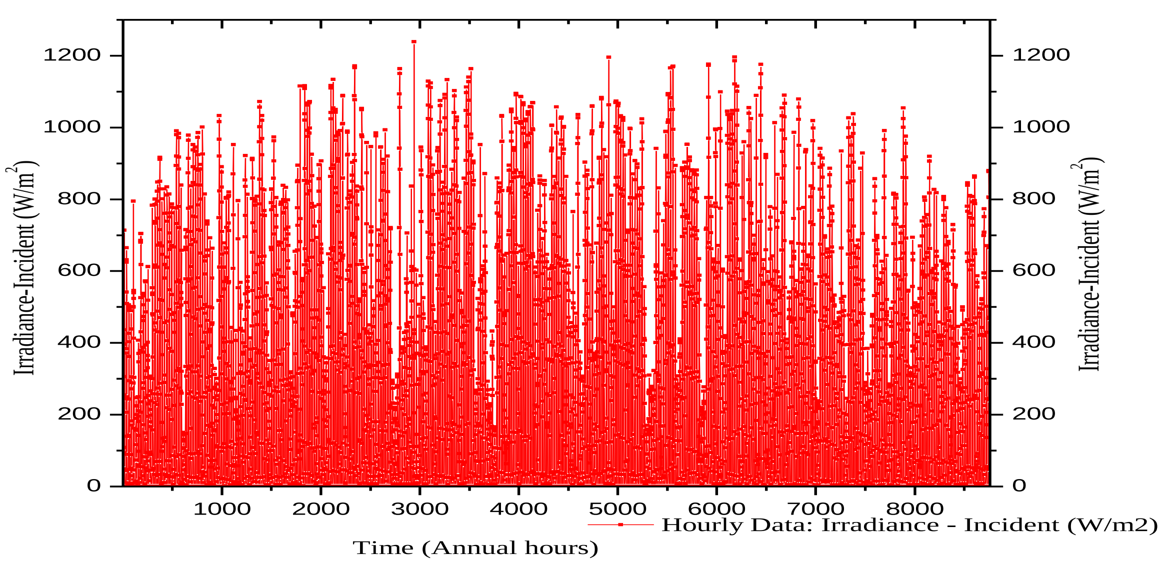



**Figure 4. 13: Annual hourly irradiance-incident (W/m$^2$)**

Though in the literature review it is noted that the ambient temperature is on average 25 ℃, meteonorm data was used to assess the ambient temperature of the site. Figure 4. 3 below shows the fluctuation of the ambient temperature based on the used meteonorm data.

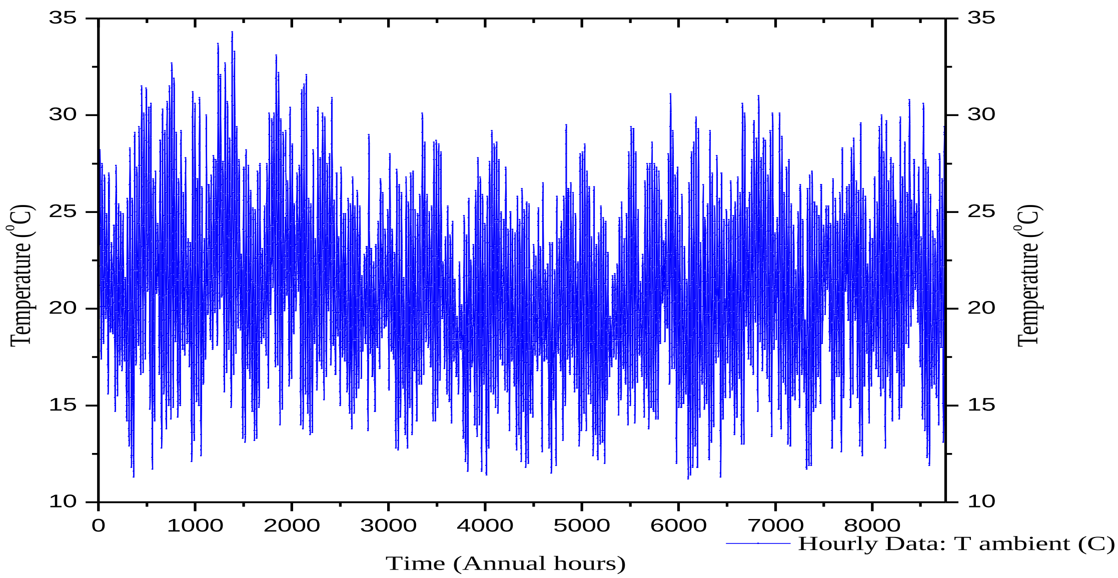



**Figure 4. 14: Fluctuation of the ambient temperature based on the used meteonorm data**

Figures 4. 2 and 4. 3 above are summarized in the annual profile of the site for an average day as shown in Figure 4. 4 below.

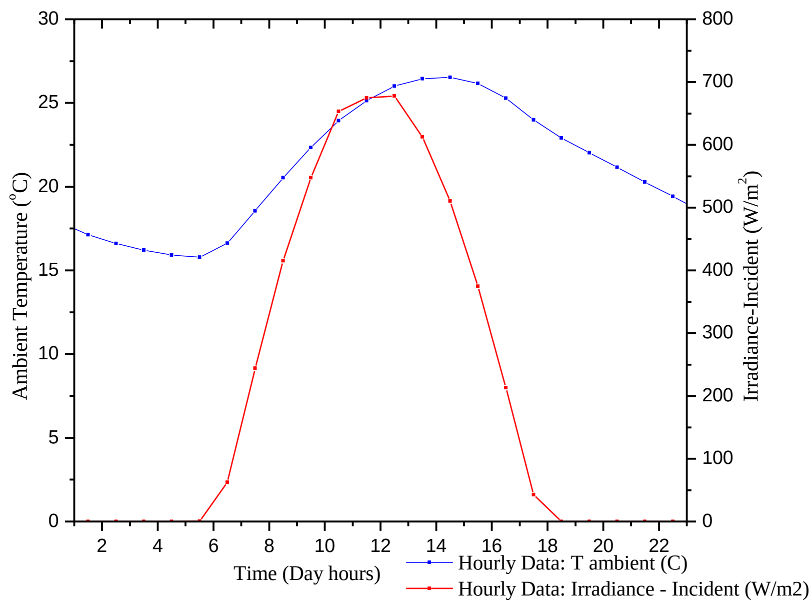



**Figure 4. 15: Annual profile of the site for the irradiance-incident (W/m$^2$) and ambient temperature (℃)**

From meteonorm data, the average ambient temperature of the study site is 21℃ which is lower than the provided ambient temperature of 25 ℃ in the literature. Thus, in this study an ambient temperature value of 21℃ was used. From the meteonorm weather data generated, the site on average has 6 sunshine hours throughout the year. Thus, its average sunshine hours are in agreement with the literature value of 6 hours at a national level.

The SAM simulation for solar collector system was repeated for different maximum tank temperatures to determine the optimal solar collector area and number of collectors required for the system.

### 4.3.3 Biogas production evaluation

It was assumed that the produced biogas complied of 60 % methane gas. Part of the produced gas is considered to be channeled and pumped back into the fermentation slurry by an external gas compressor to ensure effective slurry mixing and uniform temperature distribution in the digester while the other portion of gas is tapped off from the gas collector chamber for storage and utilization.

A user-defined model in EES was used to evaluate daily biogas production from the digester at various digester temperature and daily influent added to the digester. The relationships are discussed in chapter 5.

## 4.4 Solar-aided Anaerobic Digester System Energy Demand

The three main components, namely; anaerobic digester, solar heating system and thermal water storage tank system. These components were harmonized and integrated into one wholesome system to study its operation.

Using simulation techniques of studying and analyzing the behavior of components of the system, the system was simulated while one or more variable parameters of the system is varied to observe and record the resulting changes in other variables of the system so as to predict the behavior of the entire system.

### 4.4.1 System heat losses

The heat losses to the surrounding rely majorly on the system operating temperature and because of the continuous temperature dynamics of the different components of the system, it is complex to quantify the losses in this system.

The anaerobic digester and hot water tank were designed with structural constitution of Stainless steel, expanded polystyrene foam and concrete for insulation. The digester and water tank were simulated for different structural and insulation material thicknesses to determine their heat transfer coefficients, heat loss coefficient and rate of heat loss.

The following assumptions were taken while evaluating the heat losses in the system:

i. The thermal properties of the steel, polystyrene and concrete are constant
ii. One-dimensional heat conduction through the walls
iii. Uniform wall surface temperature
iv. Thermal contact resistance at interface is negligible
v. Radiation effects are negligible
vi. Local atmospheric pressure is 1 atm
vii. The critical Reynold number is $Re_{cr} = 5 \times 10^5$

viii. The slurry and water in the tank are static

The water storage tank oversized by 20 % in order to ensure optimal operation of the designed system with least interferences caused by heat losses.

### 4.4.2 Electric energy requirements

The system's electric energy requirements are for running the water and feed pumps and the gas compressor. Low power pumps and compressor were considered in this system such that there is no much dependence on the grid line. The feed pump at most runs for 2 hours a day to pump the influent into the digester. Only the water circulating pump and the gas compressor run throughout the day. Besides these components, the system has no other electric energy requirements.

# Chapter 5. RESULTS AND DISCUSSIONS

**Outline:**

## 5.0 Introduction

This chapter presents the results of the study and their respective discussions in relation to the set objectives of the study in their chronological order in an effort of achieving the aim of this study of designing, simulating and evaluating a solar-aided anaerobic digester system for small scale application in Uganda.

## 5.1 Anaerobic Digester System

This section discusses the study model validation, designed digester system and the digester heating system. The schematic diagram of the designed system of this study is shown in Appendix B-3. 1 of this report.

### 5.1.1 Model validation

The study digester simulation model was tested for 1 litre digester operating at average temperatures 34.8 ℃ and 35.4 ℃ with daily influent of 100 ml of yeast extract solution and hydraulic retention time of 10 days as used by Prakash [97], to evaluate its agreement with the experimental data of methane production rate and cumulative methane yield. The data used in model validation is detailed in Appendix B-1. 8 of this report.

Figures 5. 1 below shows the methane production rate curves generated using the study developed model and Prakash’s experimental data sets for digester operating at 34.8 ℃ .

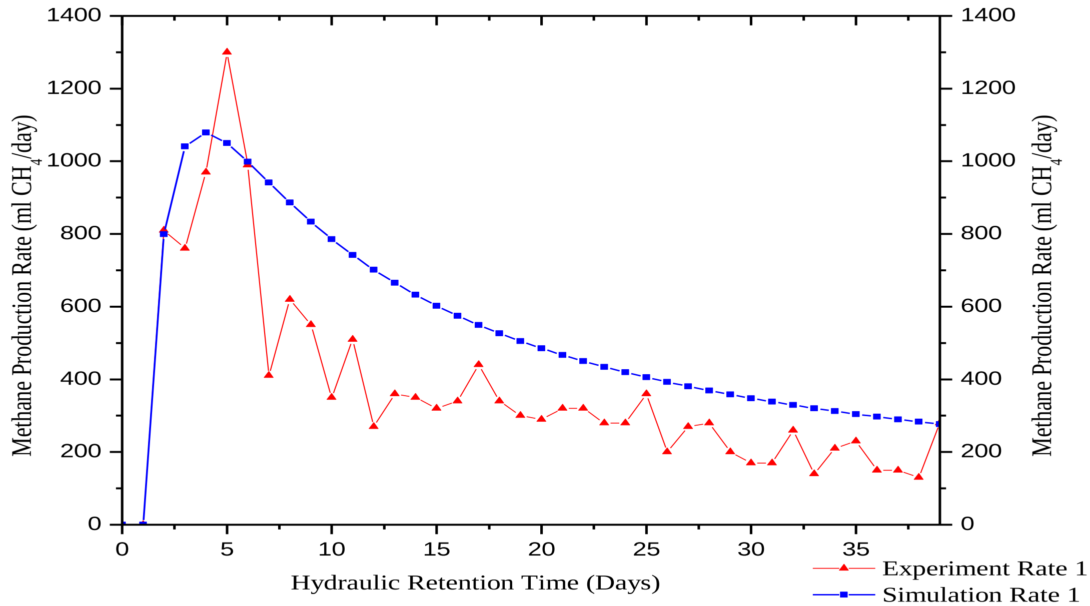



**Figure 5. 1: Methane production rate for digester system operating at 34.8 ℃**

For digester operating at 34.8 ℃, Methane production rate of Experiment 1 and Simulation 1 data have a coefficient of determination $R^2 = 75.72$ %.

Figures 5. 2 below shows the methane production rate curves generated using the developed model and Prakash's experimental data for digester operating at 35.4 ℃.

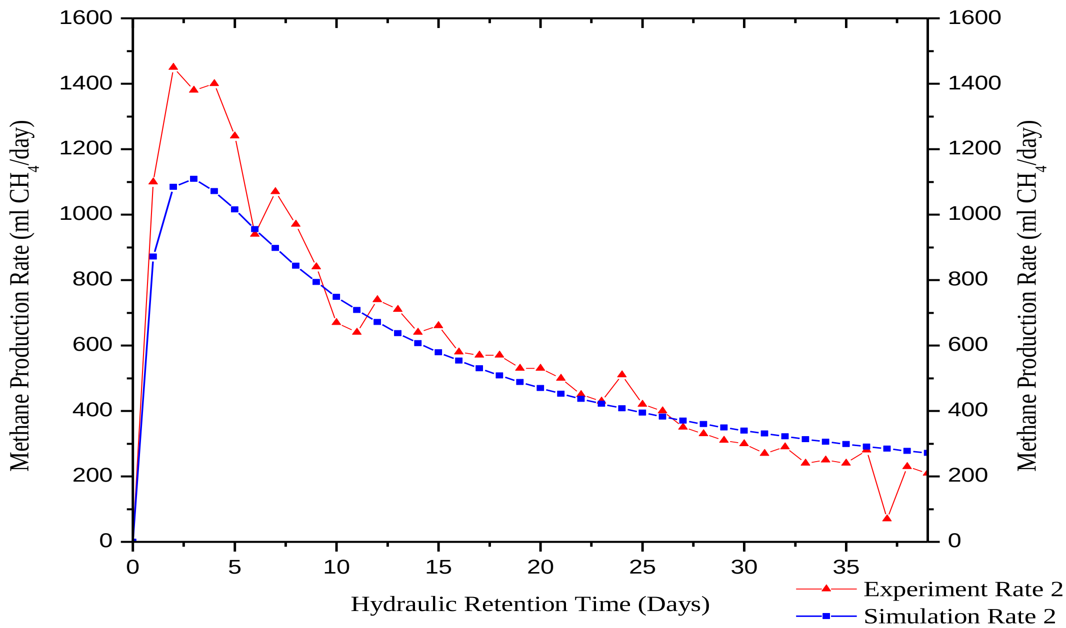



**Figure 5. 2: Methane production rate for digester system operating at 35.4 ℃**

For digester operating at 35.4 ℃, Methane production rate of Experiment 2 and Simulation 2 data have a coefficient of determination $R^2 = 95.81$ %.

Methane production rate in Experiment 2 and Simulation 2 data have a stronger coefficient of determination compared to Experiment 1 and Simulation 1 data. The lower correlation between the Experiment 1 data and simulation 1 data could be as a result of storing the substrate solution used in the experiment 1 for 2 days before being used that could have altered its volatile solid contents.

Prakash T. (2012) while treating the experimental data, determined the cumulative methane yield by summing up the respective methane production rates to that respective day under consider [97]. The same approach was used on the simulation methane production rate and compared with the model cumulative methane yield.

Figure 5. 3 below shows the cumulative methane yield by the digester operating at 34.8 ℃.

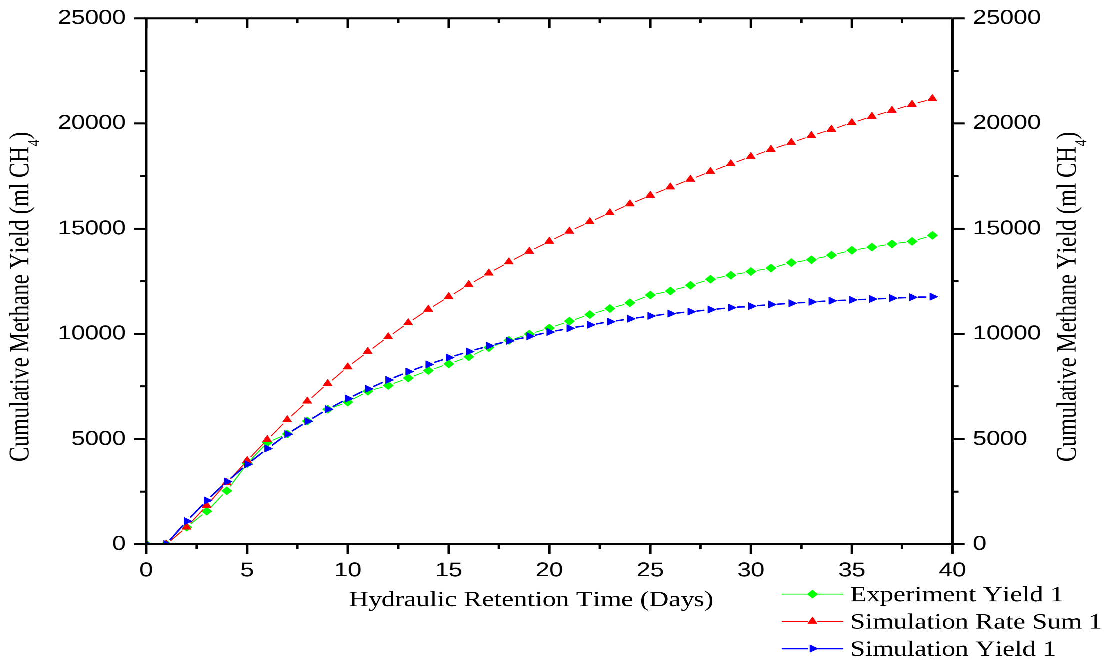



**Figure 5. 3: Cumulative methane yield for digester system operating at 34.8 ℃**

Below are the cumulative methane yield coefficients of determination for data of a digester operating at 34.8 ℃:

- Experiment yield 1 and Simulation Yield 1: $R^2 = 96.84$ %
- Experiment yield 1 and Simulation Rate Sum 1: $R^2 = 99.45$ %
- Simulation Yield 1 and Simulation Rate Sum 1: $R^2 = 95.25$ %

Figure 5. 3 below shows the cumulative methane yield by the digester operating at 35.4 ℃.

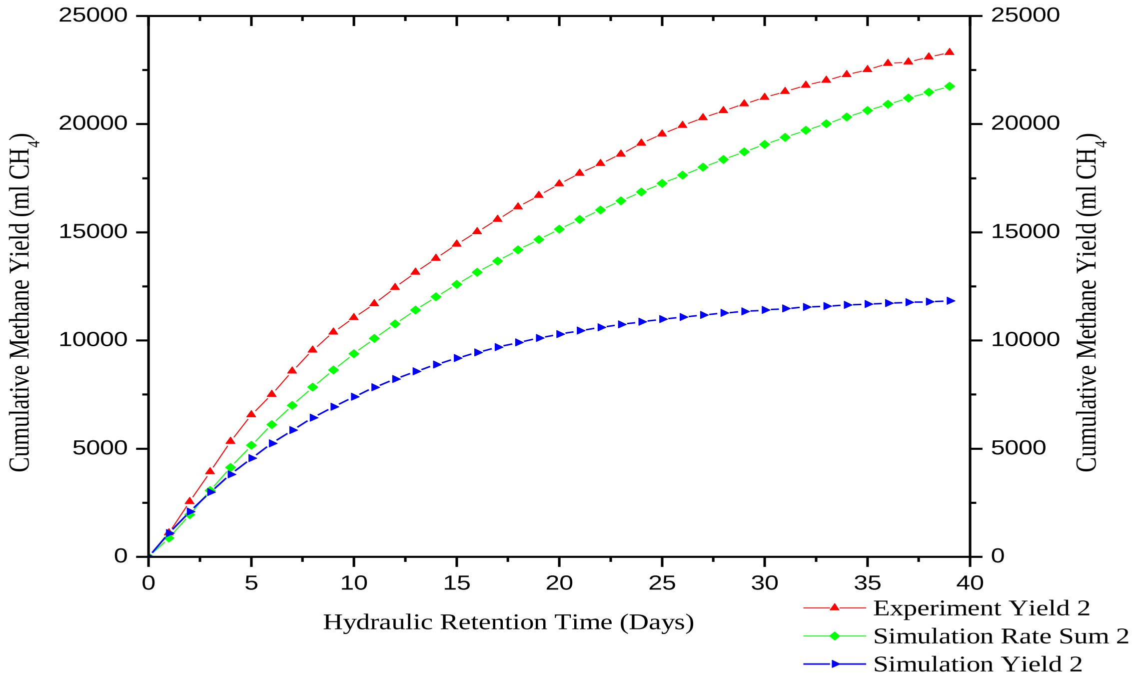



**Figure 5. 4: Cumulative methane yield for digester system operating at 35.4 ℃**

Below are the cumulative methane yield coefficients of determination for data of a digester operating at 35.4 ℃:

- Experiment yield 2 and Simulation Yield 2: $R^2 = 96.78$ %
- Experiment yield 2 and Simulation Rate Sum 2: $R^2 = 99.76$ %
- Simulation Yield 2 and Simulation Rate Sum 2: $R^2 = 95.14$ %

It can be observed for both digesters operating at 34.8 ℃ and 35.4 ℃ that there is a strongest coefficient of determination $R^2$ between the Experiment cumulative methane yield and the Simulation Rate Sum over the other considered options of data sets. Thus, the same approach of evaluating the cumulative methane yield by summing the respective methane production rates was used in this study over the approach that had been considered in the model which has a coefficient of determination of 95 % with the experimental data.

There is a wider disparity between the cumulative methane yield of Experiment 1 and the cumulative methane yield by summing the simulation methane yield rates conducted at 34.8 ℃ while the disparity is very minimal between cumulative methane yield of Experiment 2 and the cumulative methane yield by summing the simulation methane yield rates conducted at 35.4 ℃.

The wider disparity could have been caused by storage of the substrate solution for 2 days after its preparation that was used in Experiment 1.

### 5.1.2 Designed anaerobic digester system

Dimensional details of the designed digester are shown in Appendix B-1.1.1 of this report. The digester was designed for only 40 kg of cattle manure, an equivalent 62.8 % of collected cattle manure and 41% of daily livestock manure to ensure that there is no digester feedstock shortage for the at any single point throughout the year. Thus, a sum of 60 kg/day of digester influent after dilution prepared in a ratio of 2:1 of cattle manure to water. The value of 40 kg of cattle dung was considered to ease the measured for the people since they can use a 20 litre jerry can or plastic basin to estimate the feedstock. Therefore, they can use two jerry cans of cattle dung and one jerry can of water per day. The system was designed with a dependable lifetime of 30 years.

Cattle manure composition and feedstock treatment considered in this study are detailed in Appendix B-1. 2 of this report. During design and sizing, a hydraulic retention time (HRT) of 26.83 days ($\sim 27$ days) was attended when a 2.00 $m^3$ digester was sized to be fed daily with 0.06 $m^3$ fermentation slurry. HRT was attained using the digester slurry volume; the sum fermentation slurry chamber volume and the slurry layer volume of the digester, which in this case is 1.61 $m^3$.

### 5.1.2 Digester heating system

The length of copper tube required was founded to be 31.17 m ($\sim$ 31 m) for the digester of diameter 1.24 m, resulting in 8 coils of copper tube in the digester. The coils were restricted to the fermentation chamber to avoid energy wastage in heating the produced gas. Further details of the digester heating system are stated in Appendix B-1. 3 of this report.

Water mass flow rate of 44 kg/h ($\sim 0.01222$ kg/s) was considered for the system because it yielded a maximum hourly temperature change of 1.05 ℃ during the psychrophilic diapason and on average 0.4 ℃ and 0.1 ℃ during mesophilic and thermophilic diapasons, respectively when fermentation slurry was considered to be heated from 21 ℃ by hot water at 60 ℃. At this water flow rate, on average it would take at least 105 hours of heating with hot water at 60 ℃ to raise the digester fermentation slurry temperature from 21 ℃ to 50 ℃. Figure 5. 5 below shows the temperature increase and hourly temperature change for a digester slurry heated from 21 ℃ by hot water at 60 ℃.

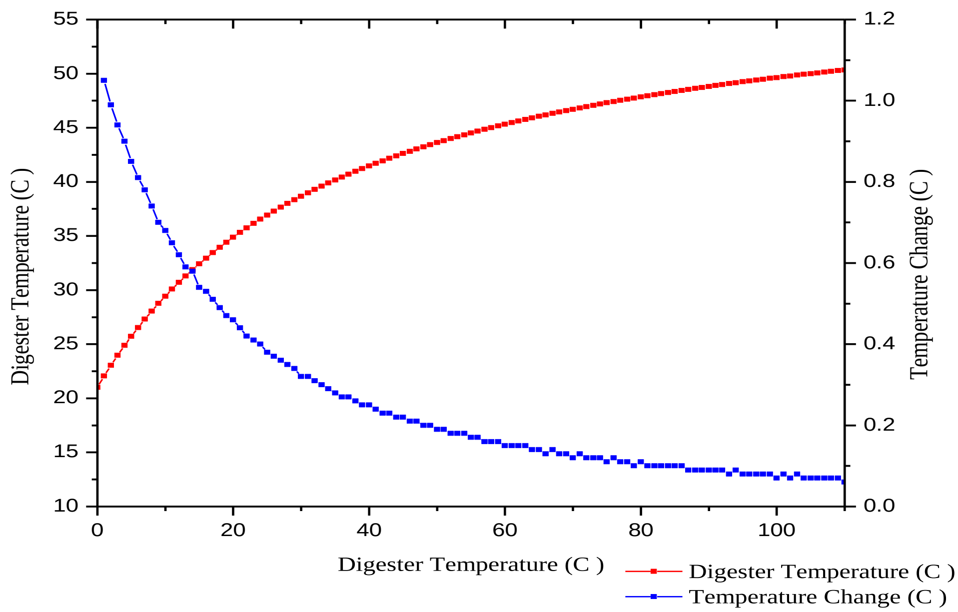



**Figure 5. 5: Digester temperature and temperature per hour at fixed hot water mass flow**

Figure 5. 5 above shows that the considered hot water mass flow rate to the digester heating system can support the digester system without affecting the thermophilic microorganism activity given their very high sensitivity to temperature changes. Since psychrophilic microorganisms are not very sensitive to temperature, a maximum temperature change of 1.05 ℃ per hour is bearable for them to survive.

## 5.2 Hot Water Storage Tank

The considered dimensions of the water tank in this study are detailed in Appendix B-1.1.2 of this report. A storage tank of 1.00 $m^3$ capacity was designed with a maximum water storage of 0.95 $m^3$. Tank dimensions are 0.93 m diameter and 1.48 m height, which is 1.6 height to diameter ratio. The details of the inlet and outlet pipe location on the tank that were used to calculate the water head pressure are shown in Appendix B-1. 3. The tank was considered to be filled through the main water supply to the level of overflow outlet, then the valves controlling the main and overflow are closed. The water tank was designed with a drainage system for casing of cleaning and maintenance.

## 5.3 Solar Collector System

The study solar collector system was simulated considering details stated in Appendix B-1. 4 of this report. From SAM software simulation, it was found that the system necessitates 5 solar water heating glazed flat plate collectors of AE-26, SRCC No. 2002001C type, each of gross area 2.35 $m^2$ to maintain the water in the storage between 51 ℃ and 60 ℃ throughout the year with the exception of few days during the worst irradiance-incident at the site that it falls to at least 47 ℃. Figure 5. 6 below shows the average daily hot water tank temperature and the ambient temperature attained from the simulated solar collector system for each month of the year.

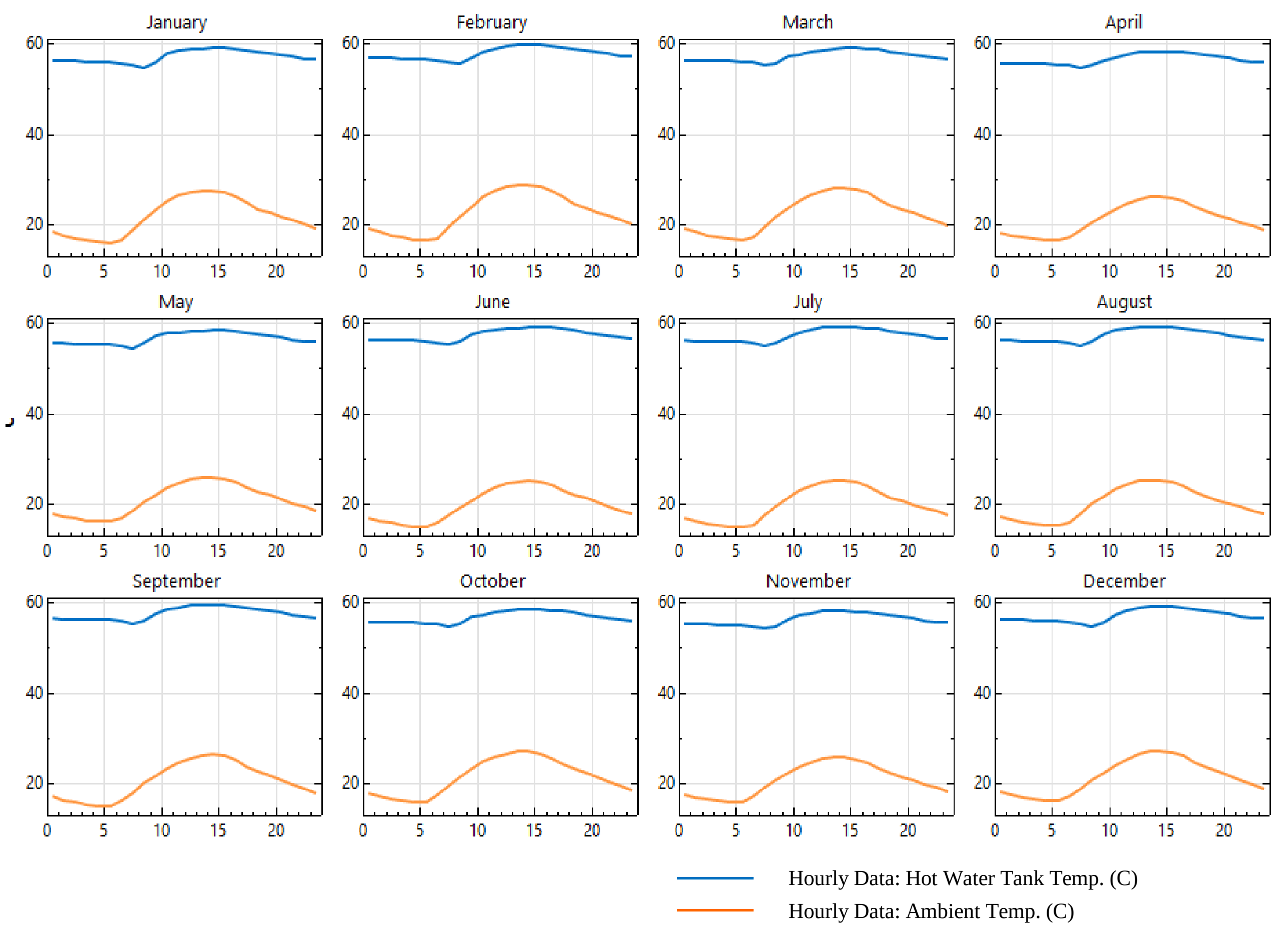



**Figure 5. 6: Monthly hot water tank temperatures and the ambient temperature**

On average, an annual profile of the daily hot water tank and ambient temperature for the designed solar collector system is shown in Figure 5. 7 below.

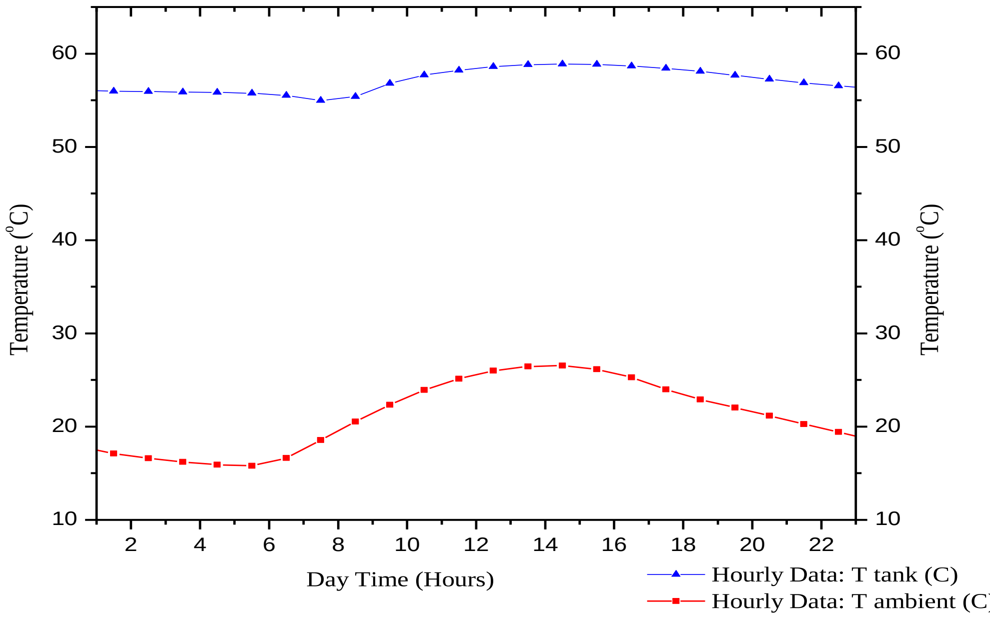



**Figure 5. 7: Annual profile of the daily hot water tank and ambient temperature**

It can be noted that by using 5 pieces of AE-26 solar water heating collectors connected in parallel at 15 ° tilt angle and 0 ° azimuth angle, the solar collector system can averagely maintain the temperature of a 1.00 $m^3$ water tank between 51 ℃ and 60 ℃ for an average water mass flow rate of 190 kg/h (~ 0.05283 kg/s ) to the thermo-siphoning solar collector system.

The designed solar collector system was found to deliver a maximum and minimum hot water temperature of 67 ℃ and 57 ℃ respectively, for the months of May and November at the site. Figure 5. 8 below shows the average daily delivered temperature from the collector system and hot water tank temperature for every month of the year as generated from the SAM simulation software.

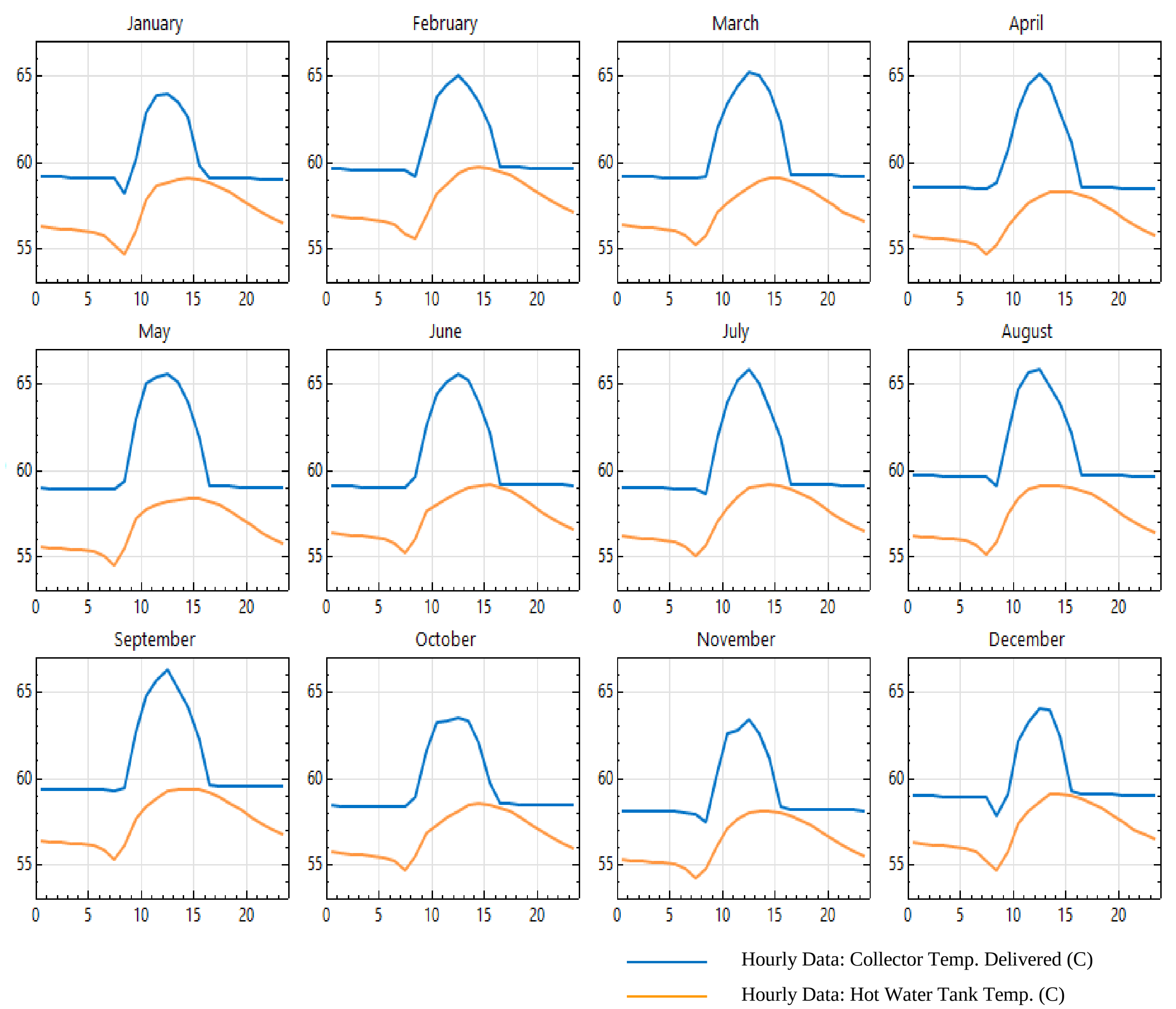



**Figure 5. 8: Daily delivered temperature from the collector system and hot water tank temperature**

From Figure 5. 8 above, it can be observed that on average, the solar collector system can sustain the hot water tank averagely above 50 °C with no other additional heating source to support it and only heating up to 60 °C in the month of February.

Figure 5. 9 below shows the annual profile of the daily solar collector delivered temperature and hot water tank temperature. On average, the solar collector system can deliver hot water at temperatures between 59 °C and 65 °C to the tank and the hot water tank temperatures vary between 55 °C and 59 °C.

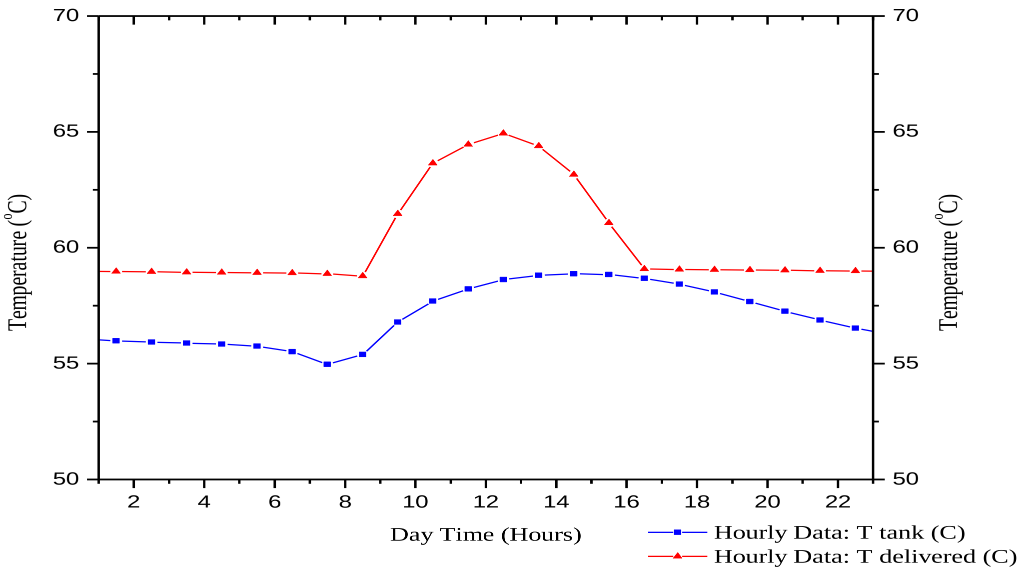



**Figure 5. 9: Annual profile of the daily solar collector delivered temperature and hot water tank temperature**

As a result of the SAM solar collector system simulation, the solar collector system water temperature variation was assessed for the 12 months of the year considering the minimum, mean and maximum delivered hot water temperatures as shown in Figure 5. 10 below.

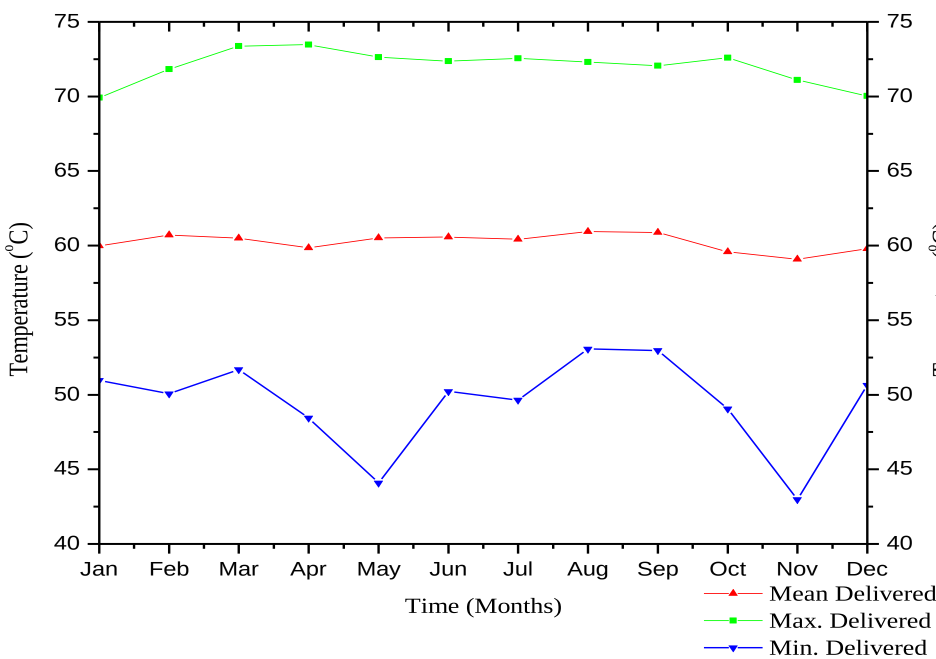



**Figure 5. 10: Solar Collector Hot Temperature throughout the year**

From Figure 5. 10 above, it can be observed that on average, the hot water from the solar collector system can attain 60 °C every month of the year at the selected site. The month of November showed the minimum collector delivered temperature of 43 °C.

With the monthly collector delivered temperatures shown in Figure 5. 9 above, the hot water tank minimum and mean temperature variations throughout the year are shown in Figure 5. 11 below.

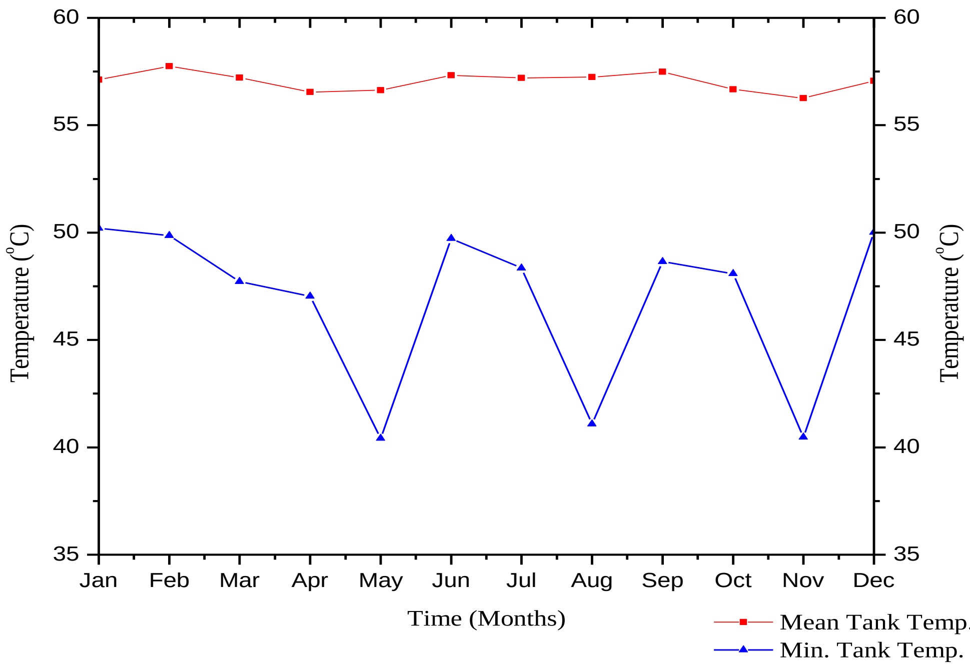



**Figure 5. 11: Monthly Hot Water Tank Temperature over the year**

From Figure 5. 11 above, it can be observed that the monthly average temperature of the hot water tank is always between 56 °C and 58 °C for all the months. It can as well be observed that the month of November still has the least average monthly hot water tank temperature of about 56 °C. The months of May and November registered the minimum hot water tank temperature of about 41 °C.

## 5.4 Gas Production

After optimization and harmonizing of the system model, the system was tested for different digester operating temperatures to evaluate the variation in gas production rate and cumulative gas yield over a period of 70 days. Figure 5. 12 below shows the gas production rate and cumulative gas yield variation with retention time for systems operating at different temperatures.

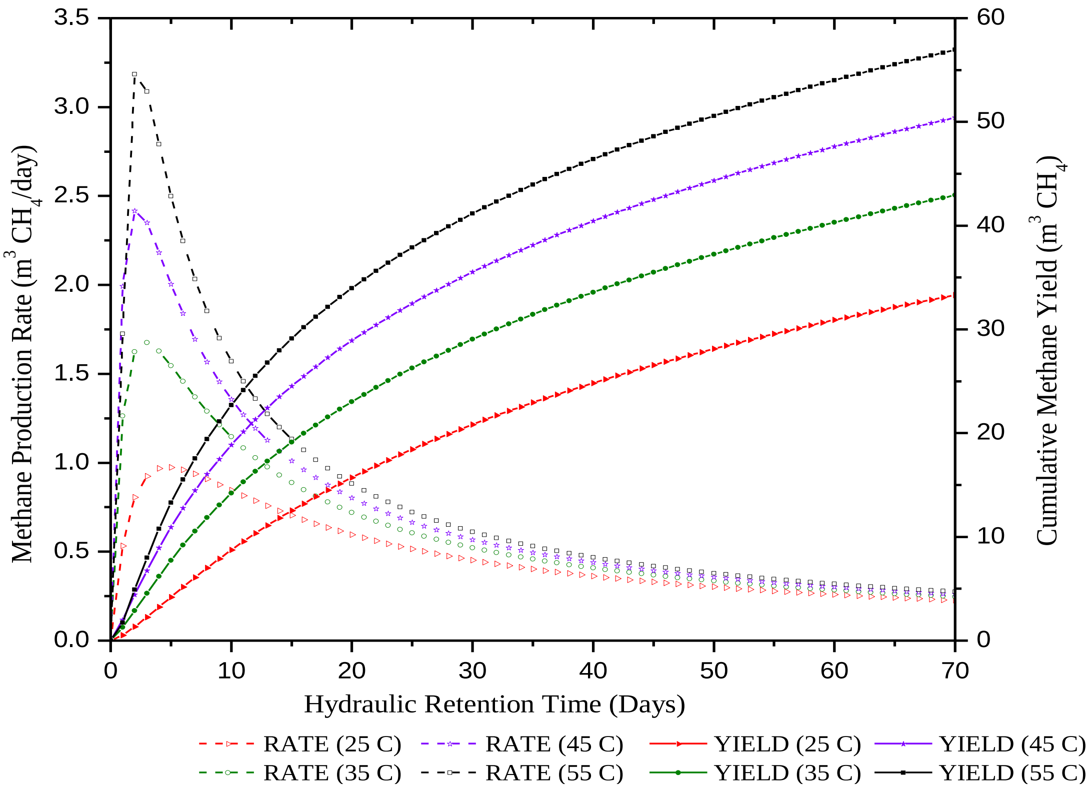



**Figure 5. 12: Digester operating at different temperatures with same daily effluent**

From Figure 5. 12 above, it can be observed that at low operating temperatures, the rate of methane production is very low and it steeply increases with increase in digester temperature in a short time. The rate of methane production spikes up in a short period of time for elevated digester temperatures and gradually decreases for all digester temperatures as retention time increases. It can also be observed that for a longer retention time, the rate of methane production is almost the same at all the different digester temperatures. These results strongly suggest that the increase in digester temperature is only effective at shorter retention time.

Also from Figure 5. 12 above, it can be observed that at shorter retention time, the cumulative methane yield disparity is minimal for different digester temperatures and only differs significantly as the retention time increases. Thus for effectiveness of the digester system, hydraulic retention time of the fermentation slurry is instrumental in attaining the balance between rate of methane production and cumulative methane yield of the digester.

From the designed digester system simulation in this study, a hydraulic retention time of 27 days was attained as result of the ratio of the reactor size of the digester designed to the daily influent fed to the system, the simulation data for the digester system attained is detailed in Appendix B-1. 9 of this report. Figure 5. 13 below shows the rate and cumulative yield of methane for the designed anaerobic digester operating at an average temperature of 50 ℃ and a digester system without heating system operating at an average ambient temperature of 21 ℃.

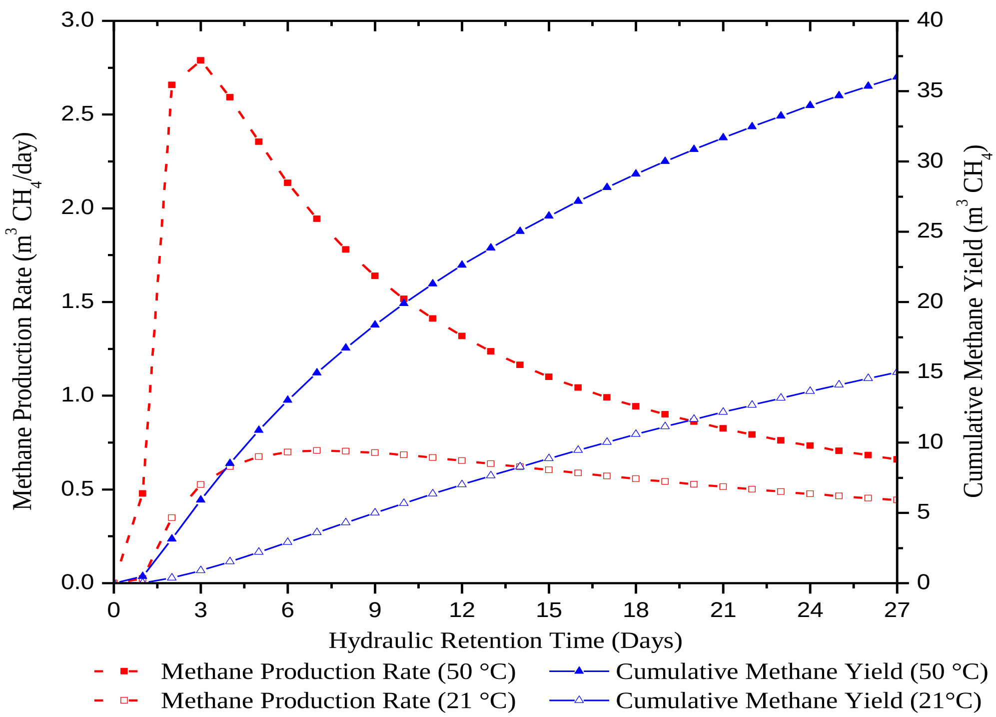



**Figure 5. 13: Methane production rate and cumulative yield of designed system at 50 ℃ and digester at 21 ℃**

By considering system design hydraulic retention time of 27 days, the digester produces a cumulative methane yield of 36.02 $m^3$ $CH_4$, thus on average producing 1.33 $m^3$ $CH_4$ per day, an equivalent of 2.22 $m^3$ of biogas[3] per day at an average operating temperature of 50 ℃ if 0.06 $m^3$ daily influent supply maintained. If the digester system was to operate at the ambient temperature, averagely 21 ℃, it would produce 0.93 $m^3$ of biogas per day.

[3] Methane gas produced $\equiv 0.6 \times$ Biogas produced

At hydraulic retention time of 27 days, 64 % of volatile solids in the digester sludge are removed from the slurry, an equivalent of 3.2 kg out of 5.1 kg volatile solids in daily influent fed into the digester. Figure 5. 14 below shows the variation of volatile solids reduction with hydraulic retention time in anaerobic digester operating in thermophilic temperature range.

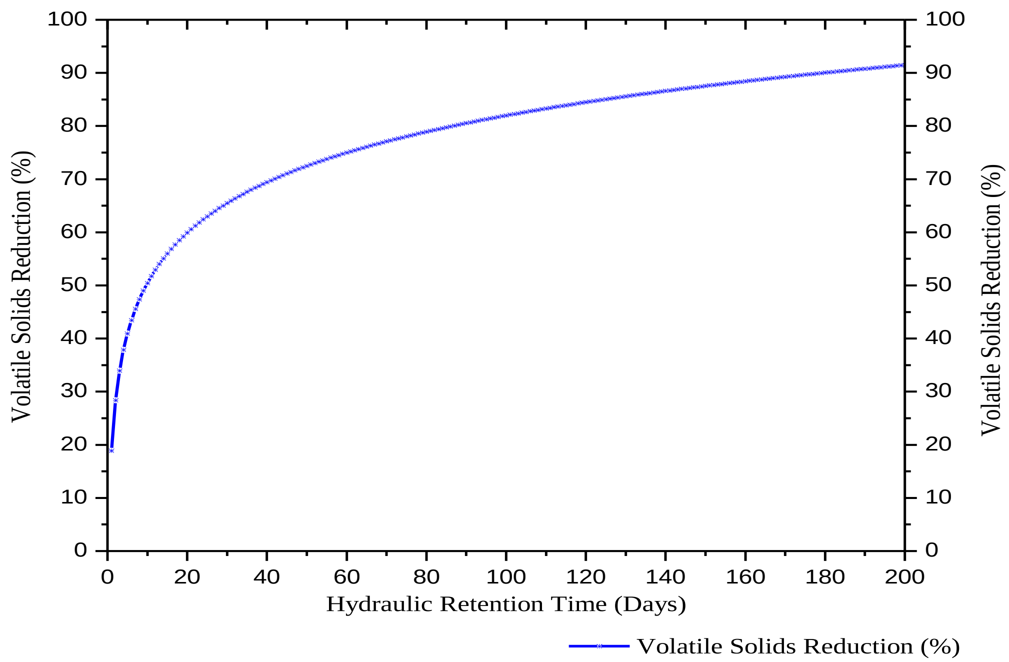



**Figure 5. 14: Volatile Solids Reduction by the designed system**

From Figure 5. 14 above, it can be observed that the longer the hydraulic retention time the more volatile solids are reduced from the digester sludge. By the 10$^{th}$ day of hydraulic retention, 50 % of volatile solids are already removed from the sludge and beyond 10 days of slurry retention, the rate of volatile solids reduction slows down. Since volatile solids are responsible for methane production, their removal from sludge reduces the sludge GHG emissions once they are egested from the digester.

Incorporation of a solar collector heating system to the anaerobic digester to raise the digester operating temperature from 21 °C to 50 °C resulted in an average daily increment in biogas production of 1.29 $m^3$ from the digester. Thus operating the digester at 50 °C resulted in more than double (2.4 times) the daily average biogas production for a digester operating at 21 °C.

## 5.5 System Temperature Variation

The solar-aided anaerobic digester system was evaluated for the worst irradiance-incident case, when the hot water storage minimum temperatures fall below 50 ℃ to evaluate its effect on the digester temperature. Figures 5. 15 and 5. 16 below show the behavior of the digester for the period of 5 days from 28th May to 1st June (annual hours range from 3529 to 3648) and from 14th November to 18th November (annual hours range from 7609 to 7729), respectively.

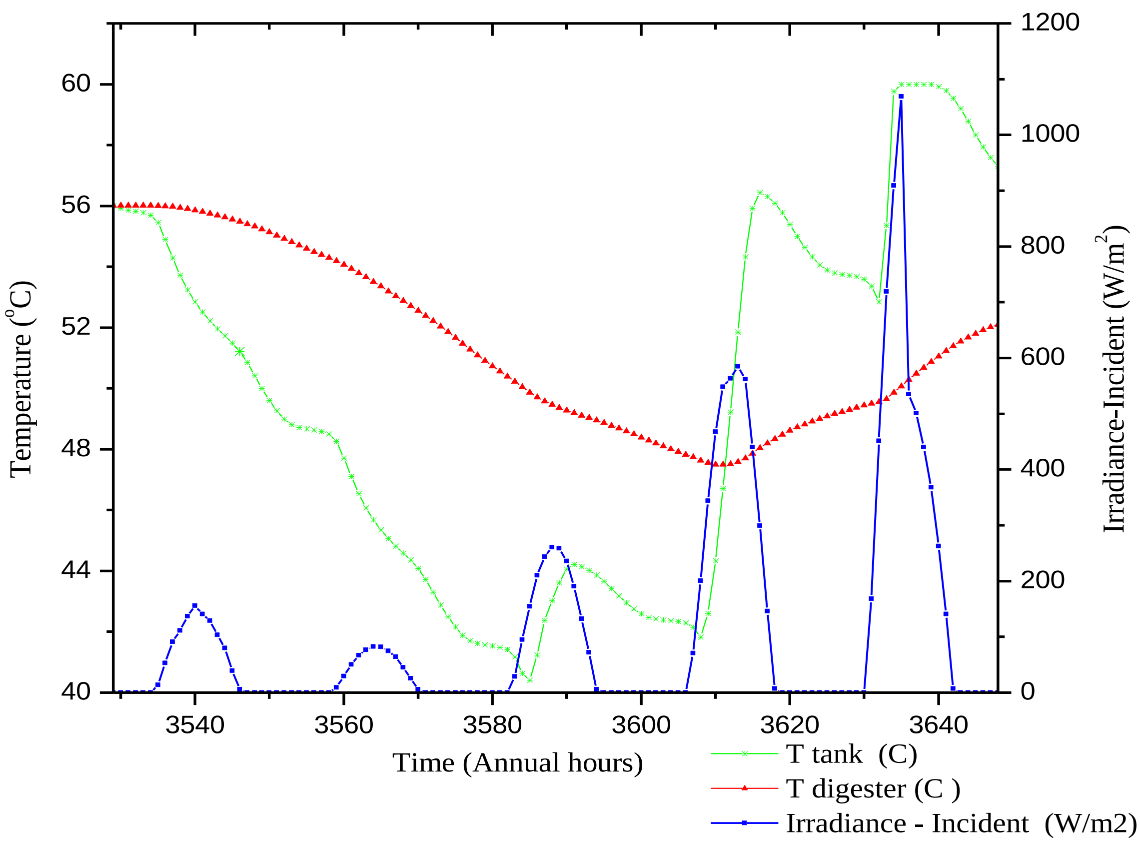



**Figure 5. 15: Temperature variation of the system during the worst Irradiance- Incident period of May 28th to June 1st**

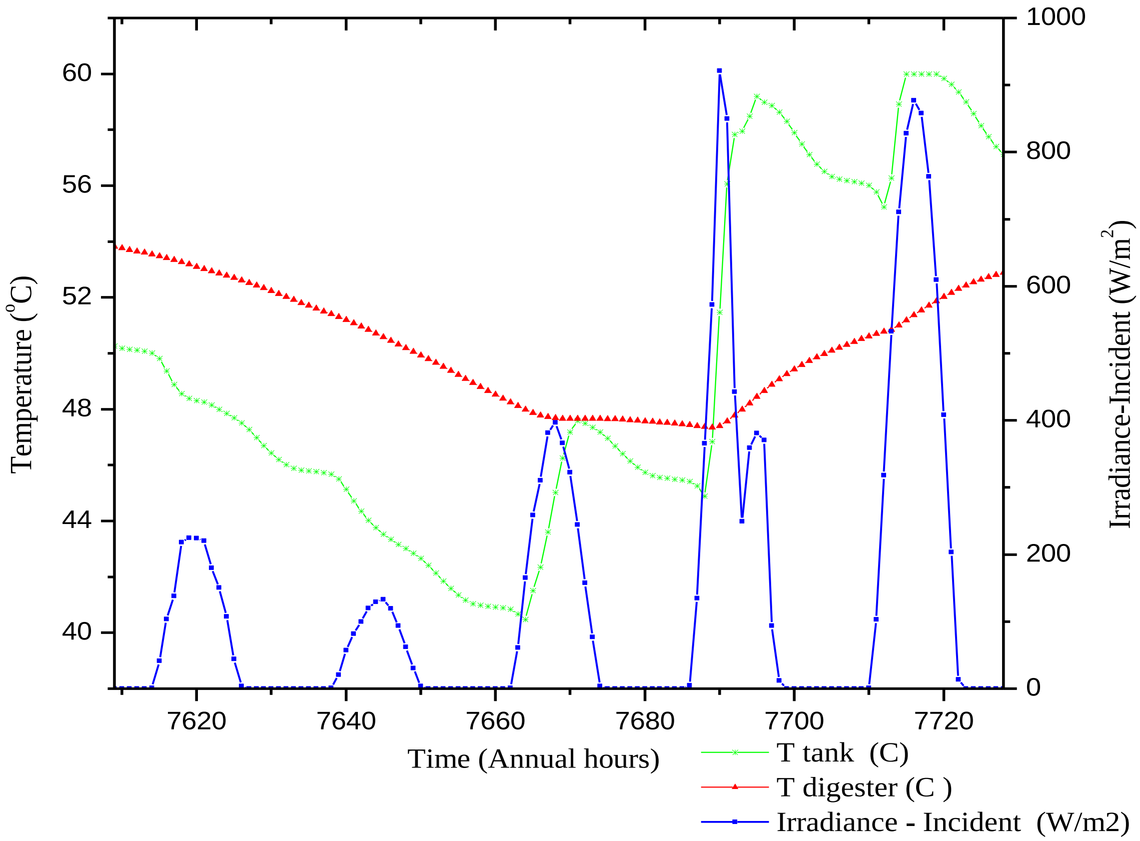



**Figure 5. 16: Temperature variation of the system during the worst Irradiance- Incident period of November 14th to November 18th**

From Figures 5. 15 and 5. 16 above, it can be observed that even during the worst irradiance-incident conditions, the digester only falls to about 47℃, thus still operating in the thermophilic temperature range. On average, it takes 6 hours for the digester temperature to fall by 1℃ during the worst operating period of the digester system.

The system was as well evaluated for the best irradiance-incident period and the relationship shown in Figure 5. 17 below was obtained. It represents 11 days from April 2nd to April 12th (annual hours range from 2185 to 2448).

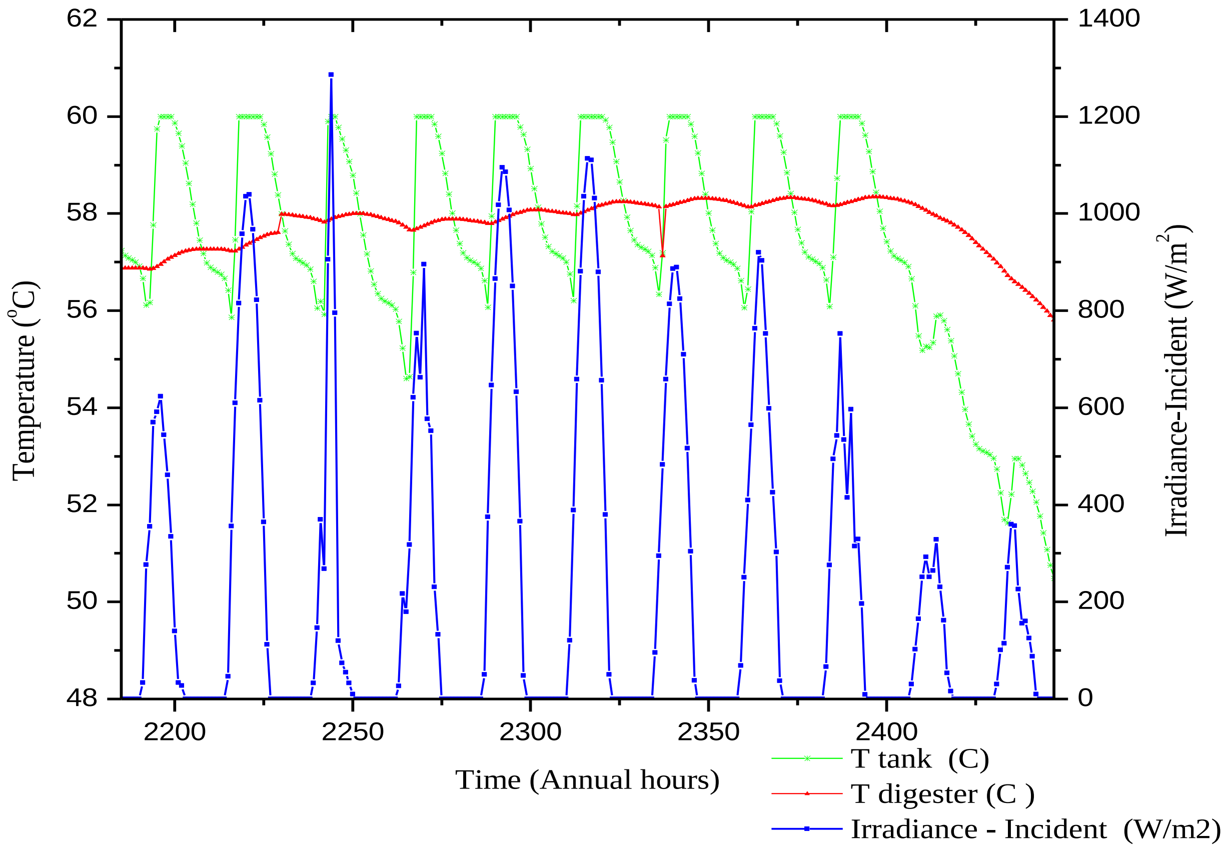



**Figure 5. 17: Temperature variation of the system during the best Irradiance- Incident case**

From Figure 5. 17 above, it can be observed that the digester operating temperature is maintained above 55 °C and 60 °C, at the best irradiance-incident the digester temperature never exceeds 58.5°C and on average, it takes 10 hours for the digester temperature to raise by 1 °C during the best irradiance-incident period.

From Figures 5. 15, 5. 16 and 5. 17 above, the digester temperature ranges between 47 °C and 58.5 °C throughout the year, on average taking a minimum of 6 hours for the digester temperature to raise by 1 °C for the designed system in this study in all seasons of its operation throughout the year.

The system also evaluated for cases of varying hot water flow rates in comparison to the design flow rate of 44 kg/h. A day during best and worst irradiance-incidence periods were considered and simulated for the respective digester temperature and hot water flow rate.

Figure 5. 18 below shows the variation of hot water tank temperature and the necessary hot water mass flow rate variation for 2nd April a day during best irradiance-incidence period for the study site in order to maintain the digester operating temperature at averagely 50 ℃.

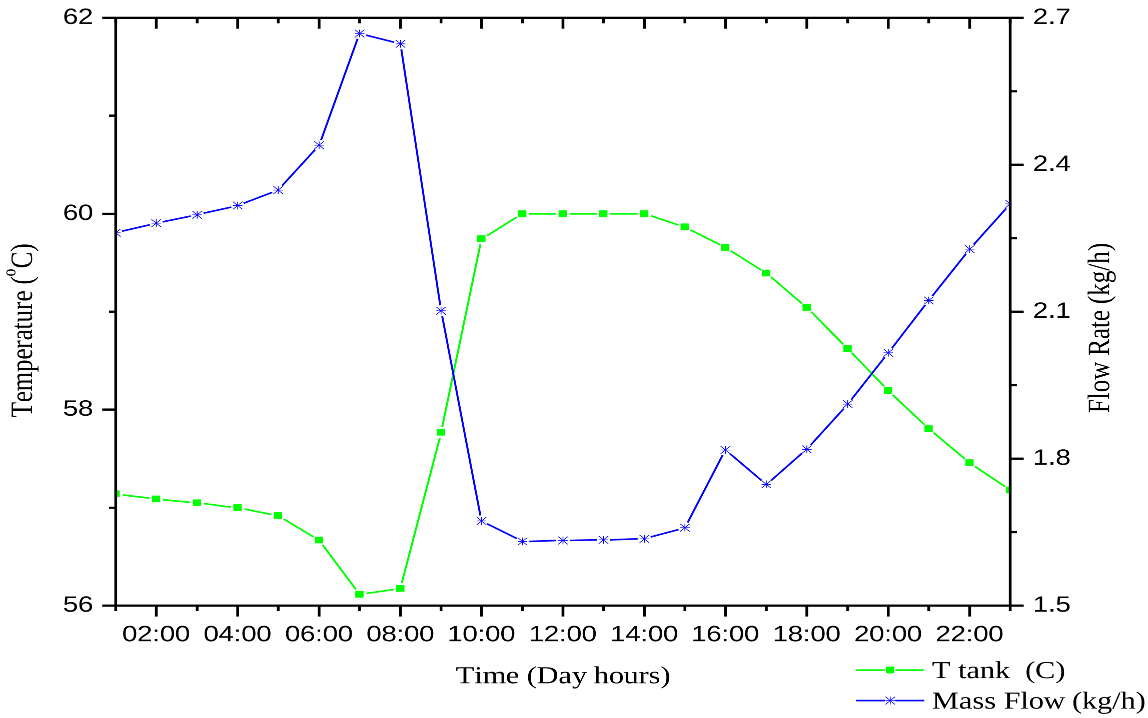



**Figure 5. 18: Temperature and flow rate variation for 2nd April**

From Figure 5. 18 it can be observed that for the digester temperature can averagely be maintained at 50 ℃, there is a wider variation in hot water flow rate over the course of the day. The average hot water flow rate required during the best irradiance-incidence period to maintain the digester temperature at 50 ℃ was found to be 2.1 kg/h which results in less than 1 ℃ temperature raise per day.

Figure 5. 19 below shows the variation of hot water tank temperature and the necessary hot water mass flow rate variation for 14th November a day during worst irradiance-incidence period for the study site in order to maintain the digester operating temperature at averagely 50 ℃.

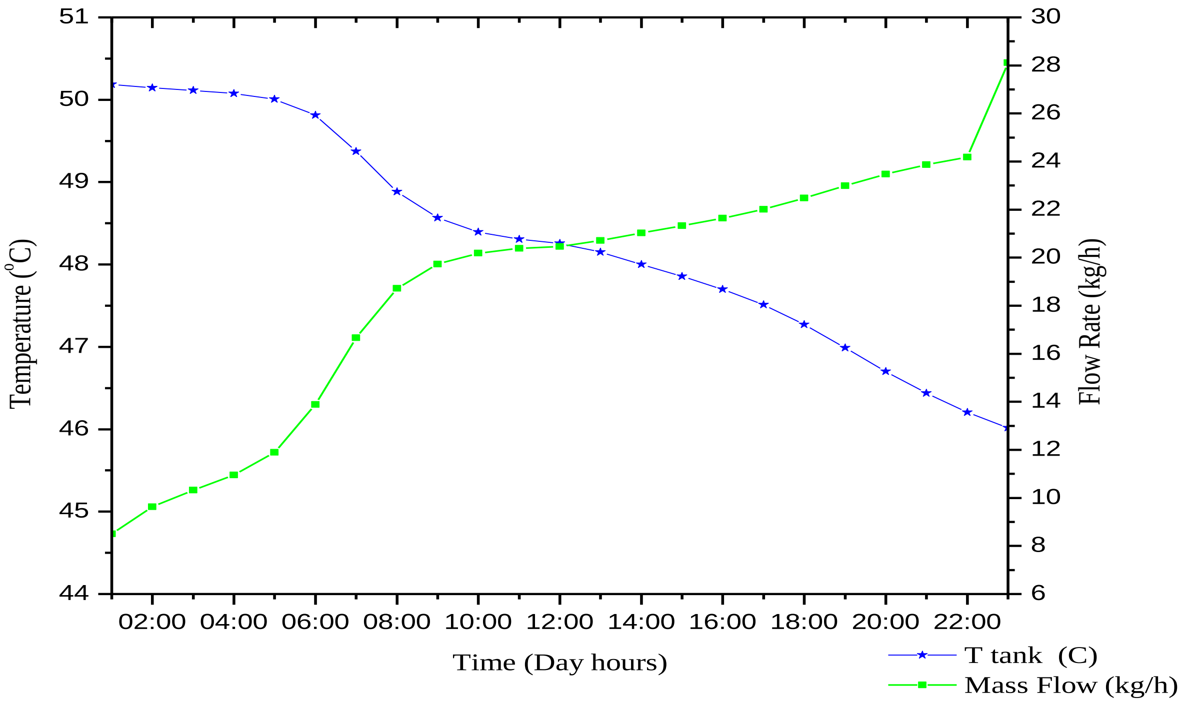



**Figure 5. 19: Temperature and flow rate variation for 14th November**

From Figure 5. 19 above, it can be observed for the digester temperature can averagely be maintained around 50 ℃, there is a wider variation in the hot water flow rate required over the course of the day. The average hot water flow rate required during the best irradiance-incidence period to maintain the digester temperature at 50 ℃ was found to be 18.3 kg/h which also results in less than 1 ℃ temperature raise per day.

Maintaining the digester operating temperature 50 $\pm 1$ ℃ for all irradiance-incidence periods is a challenge because different hot water flow rates are required for different periods of the year for microorganism activity stability and effectiveness in the digester. Thus, the digester temperature variation should be maintained at minimal as possible since the thermophilic methanogens are very sensitive to temperature changes.

## 5.6 System Heat Losses

In the evaluation of the system heat losses of the designed system, details considered are stated in Appendix B-1. 5 of this report. The digester and hot water storage tank were designed with the same structural and insulation thicknesses detailed in Table 5. 1 below to ensure minimal heat losses to the surrounding across their walls:

**Table 5. 1: Material thickness for designed anaerobic digester and hot water tank**

| Material | Thickness (m) | Description |
|---|---|---|
| Stainless steel | $2.5 \times 10^{-3}$ | Structural material |
| Expanded Polystyrene Foam | 0.1 | Insulation material |
| Concrete | 0.2 | Insulation material |

The surface area of the designed digester and water tank were found as $4.63\ \mathrm{m^2}$ and $5.67\ \mathrm{m^2}$ respectively, and the overall heat transfer coefficient for the designed digester and water tank in this study at the stated wall thicknesses in Table 5. 1 was $0.08\ \mathrm{W/m^2\ ℃}$ and the rate of heat loss from the digester and water tank were found to be $0.37\ \mathrm{W/℃}$ and $0.45\ \mathrm{W/℃}$, respectively.

Considering the digester and the water tank operating at an average temperature of 50 ℃ with an average ambient temperature of 21 ℃ and wind speed of 2.6 m/s, the digester and water tank surface temperature were found to be 21.4 ℃, which varies at the tank temperatures vary.

The system was simulated for the worst irradiance-incident period for 5 days from 14th November to 18th November to evaluate the variation of the surface temperature for varying interior temperature and ambient temperature during this period. The weather and system data for this period is detailed in Appendix B-2. 1 of this report. Figure 5. 20 below shows the variation in digester/tank and surface temperature with time.

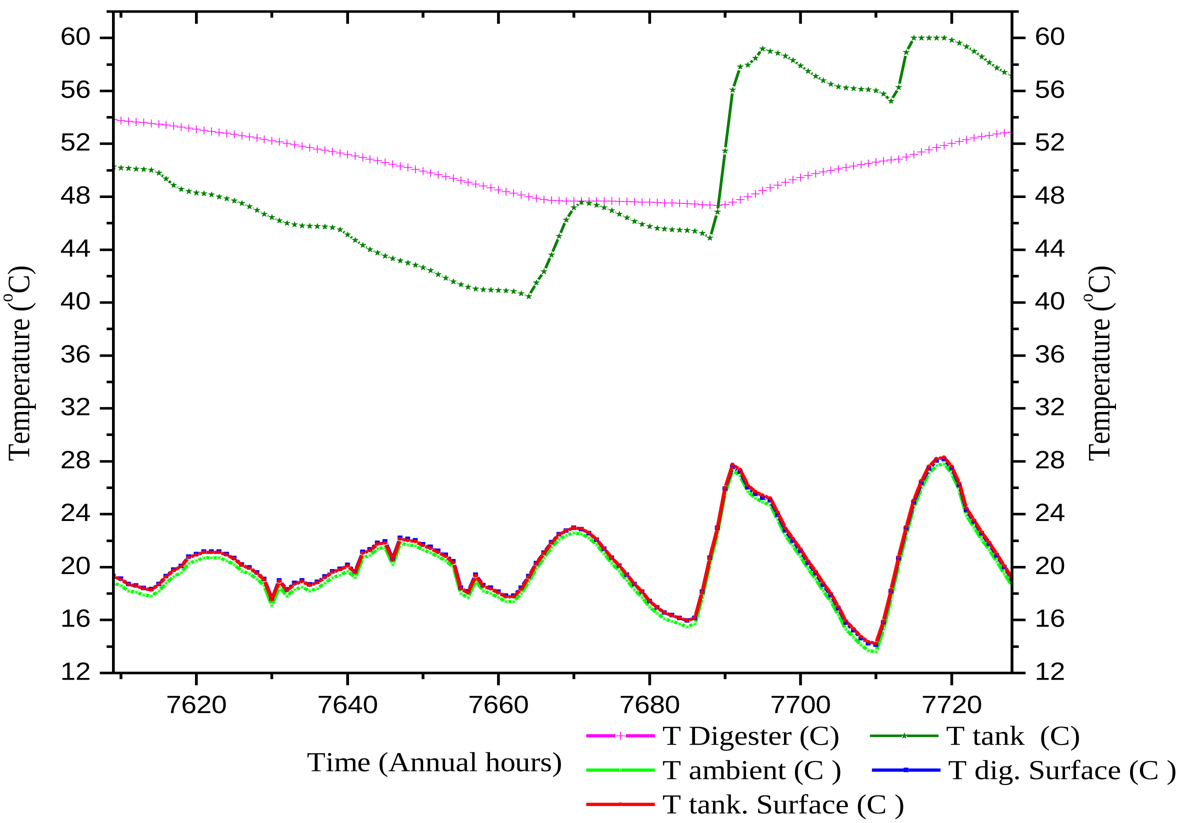



**Figure 5. 20: Digester and hot water tank surface temperature at varying ambient temperature**

From Figure 5. 20 above, it can be observed that both the digester and water tank surface temperatures are approximately equal to the ambient temperature. The heat losses are not fixed but vary basing on the temperature of the digester/tank and the ambient temperature.

The system was simulated for the worst irradiance-incident period for 5 days from 14$^{th}$ November to 18$^{th}$ November to evaluate the heat loss from the digester and water tank at varying irradiance-incident in this period. Figure 5. 21 below shows the heat losses from the digester and tank with time as irradiance-incident varies.

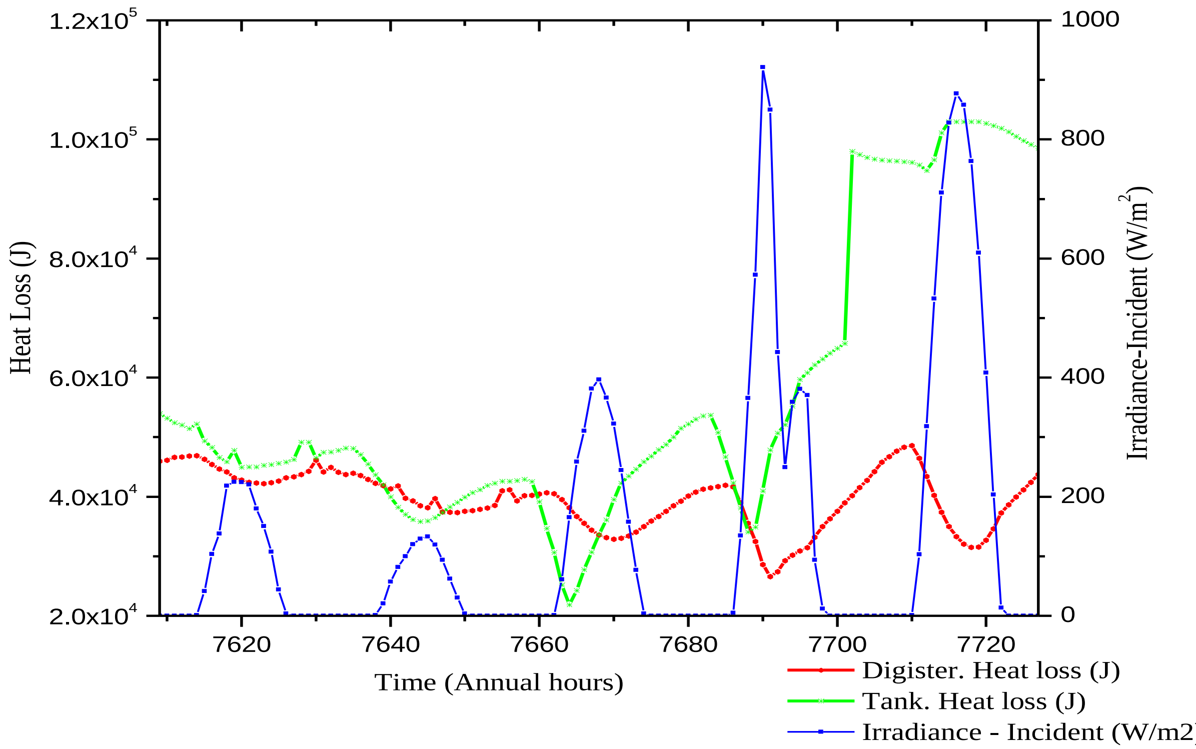



**Figure 5. 21: Heat losses from the digester and tank with time as irradiance-incident varies**

From Figure 5. 21 above, it can be observed that the heat losses from the water tank increase drastically as the irradiance-incident increases because the water temperature increases, thus resulting a greater temperature change between the water and surface temperature.

In order to cater for the heat losses in the system, the system water tank was designed with an allowance of 20 % to ensure that the system's operating conditions are not interfered by the heat losses from the system at any moment.

## 5.7 Influent Flow Effect

The introduction rate of the influent to the anaerobic digester was evaluated to assess its impact on the digester fermentation slurry temperature. The Influent was considered to be at 21 ℃, ambient temperature and being introduced to the digester operating on average at 50 ℃. Figure 5.22 below shows the variation in the digester temperature and change in temperature caused by introducing the influent for a specific period of time.

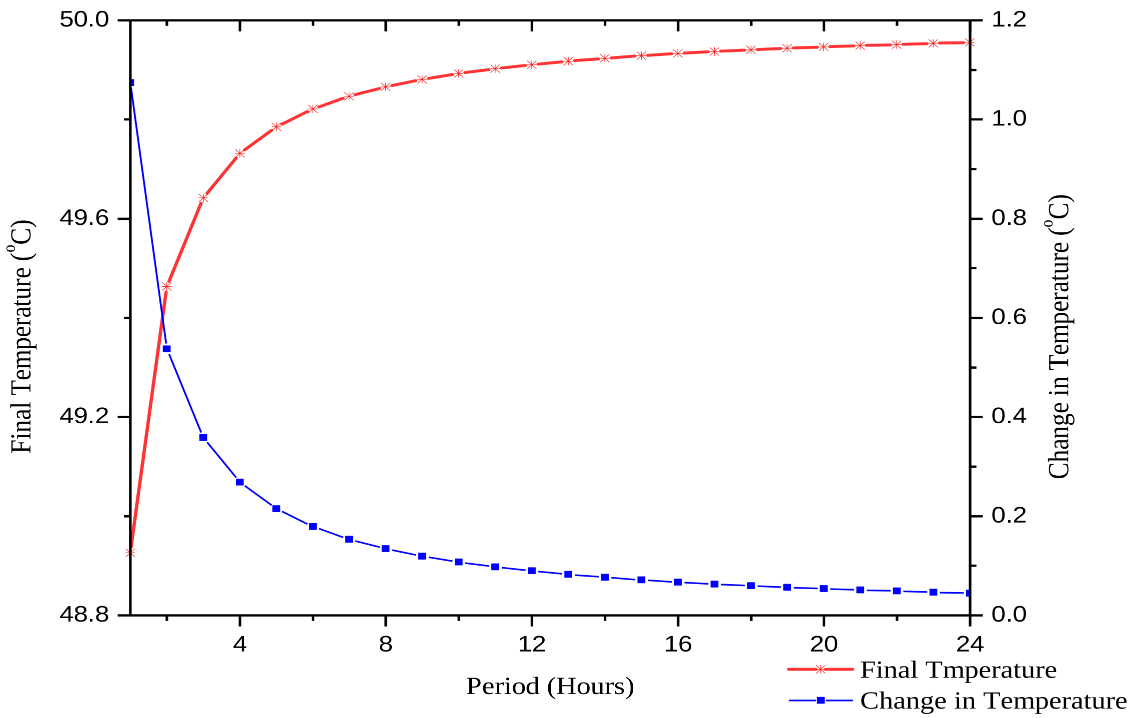



**Figure 5. 22: Influent effect on digester temperature**

From Figure 5. 22 above, it can be observed that introducing the whole sum of 0.06 $m^3$ in one hour would result in 1.074 ℃ change in the digester temperature. Since thermophilic methanogens are very sensitive to temperature changes, feed introduction should take at least more than one hour to minimize the temperature variation in the digester. However, it should be noted that pumping of the influent consumes energy, thus longer duration of pumping increases the operation and maintenance costs of the system.

## 5.8 Feasibility Analysis

Prices of components used in this study were obtained from the updated list of prices of 2014 published by the Public Procurement and Disposal of Public Assets Authority (PPDA) of Uganda [103], with the exception of the glazed flat plate water heater collector whose default price in SAM software was used. The prices were treated to an inflation rate of 5.4 % and the investment loan acquired at a commercial bank lending interest rate of 24.23 % for 2016 obtained from Bank of Uganda (BoU) and the monetary fund in dollars[4] were converted to Uganda shillings using the central bank exchange rate [104]. The investment cost was considered as 50 % loan taken for a period of 10 years. The biogas Feed in Tariff was obtained from the Uganda Renewable Energy Feed-in Tariff (REFIT) Phase 2 Guidelines as 0.115 $\mathrm{USD/kWh_{eq.}}$ an equivalent of 386.92 $\mathrm{UgShs/kWh_{eq.}}$ [105].

The feedstock, land requirement and water were not priced because they were considered to be available to every household. The fluctuation in cattle manure composition and digester system degradation over time were ignored in this study. Details of equipment costing used in this study are detailed in Appendix B-1. 6 of this report.

The investment cost of a solar-aided anaerobic digester system and digester system without heating system was 16, 487, 708.69 UgShs and 3, 552, 633.826 UgShs, respectively. The systems were considered to have annual operation and maintenance cost of 0.3 % of investment cost, an equivalent of 49, 463.13 UgShs and 10, 657.9 UgShs, respectively. Insurance was evaluated at 0.2 % of the respective investment cost of the system as given in the Public Procurement and Disposal of Public Assets Authority (PPDA) of Uganda.

Two aboveground anaerobic digester systems were considered in this feasibility analysis having the same digester design, size and construction material composition with a productive period of 30 years and constructed above the ground. The considered systems are:

- Study designed solar-aided anaerobic digester system operating at averagely 50 ℃
- Anaerobic digester without solar heating system operating at average ambient temperature of 21℃

Details of financial analysis of the two considered systems are shown in Appendix C-3. 1 of this study report showing costs and benefits for the systems for the period of 30 years.

Figures 5. 23 and 5. 24 below, show the cash flows of a solar-aided anaerobic digester system and anaerobic digester system without heating incorporation for a period of 30 years, respectively.

[4] 1 USD≡3364.52 UgShs

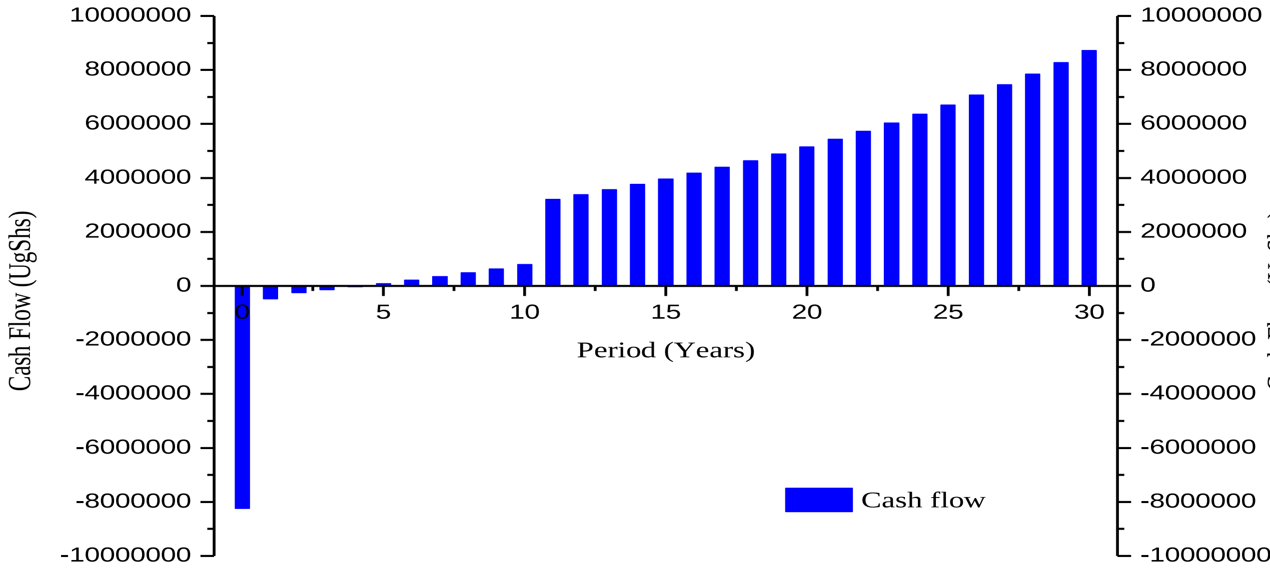



**Figure 5. 23: Cash flow of a designed solar-aided anaerobic digester system**

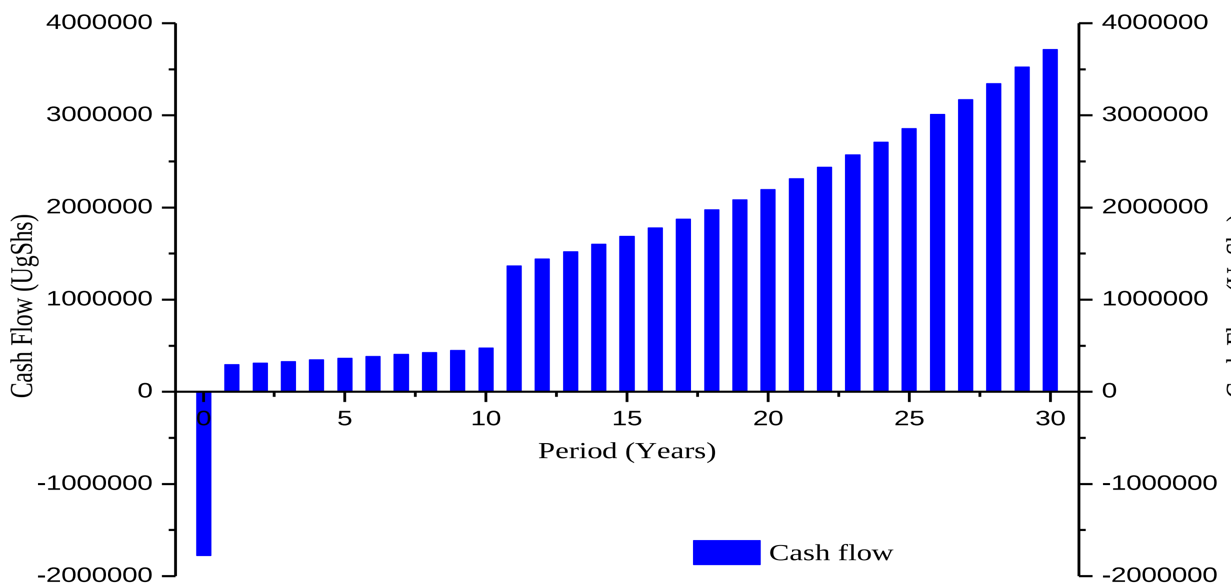



**Figure 5. 24: Cash flow anaerobic digester system without heating**

From both Figures 5. 23 and 5. 24 above, it can be observed that the revenue is low for the first 10 years of the two plants, this is because of the annuities that have to be paid in order to clear the loan share of the investment cost of the systems. The levelized cost of energy (LCOE) for the designed solar-aided anaerobic system was found to be $227.78\ UgShs/kWh_{eq.}$ for a plant lifetime of 30 years, an equivalent of $0.0677\ USD/kWh_{eq.}$, a value lower than the Feed-in Tariff of $386.92\ UgShs/kWh_{eq.}$ for project invested at 50 % loan, an equivalent of 8, 243, 854.347 UgShs and the other portion as equity.

The LCOE for the digester system without heating system incorporation was found to be $117.82\ UgShs/kWh_{eq.}$ for a plant lifetime of 30 years, an equivalent of $0.035\ USD/kWh_{eq.}$. This project is more feasible because of its very low LCOE to that a solar-aided anaerobic digester system. However, it has a lower daily biogas production.

Table 5. 2 below shows the economic analysis of the two considered systems evaluated at 50 % loan of the investment cost.

**Table 5. 2: System feasibility analysis two anaerobic digester systems**

| Anaerobic Digester System | LCOE (UgShs/kWheq.) | Cost-Benefit Ratio | Payback Period (years) | Annuity (UgShs) |
|---|---|---|---|---|
| **With Solar Heating (at 50 ℃)** | 227.78 | 0.589 | 10.2 | 2, 255, 054.022 |
| **Without Heating (at 21 ℃)** | 117.82 | 0.305 | 6 | 485, 900.215 |

From Table 5. 2 above, it can be observed that both anaerobic digester system feasible for the considered site because of their low cost benefit ratio and a short payback period in addition to a low LCOE. The study designed anaerobic digester system is more feasible because of its higher daily biogas production compared to the other system operating at 21 ℃.

The current interest rate of 24.23 % of loans in the country is too high for projects that would rely on loans for their implementation. The two digester systems were evaluated for different loan share percentages of the investment cost to examine its effect on their feasibility in Uganda. Figure 5. 25 below shows the effect of investment loan share percentages on LCOE and Cost-Benefit Ratio for a solar-aided digester system and digester system without heating system.

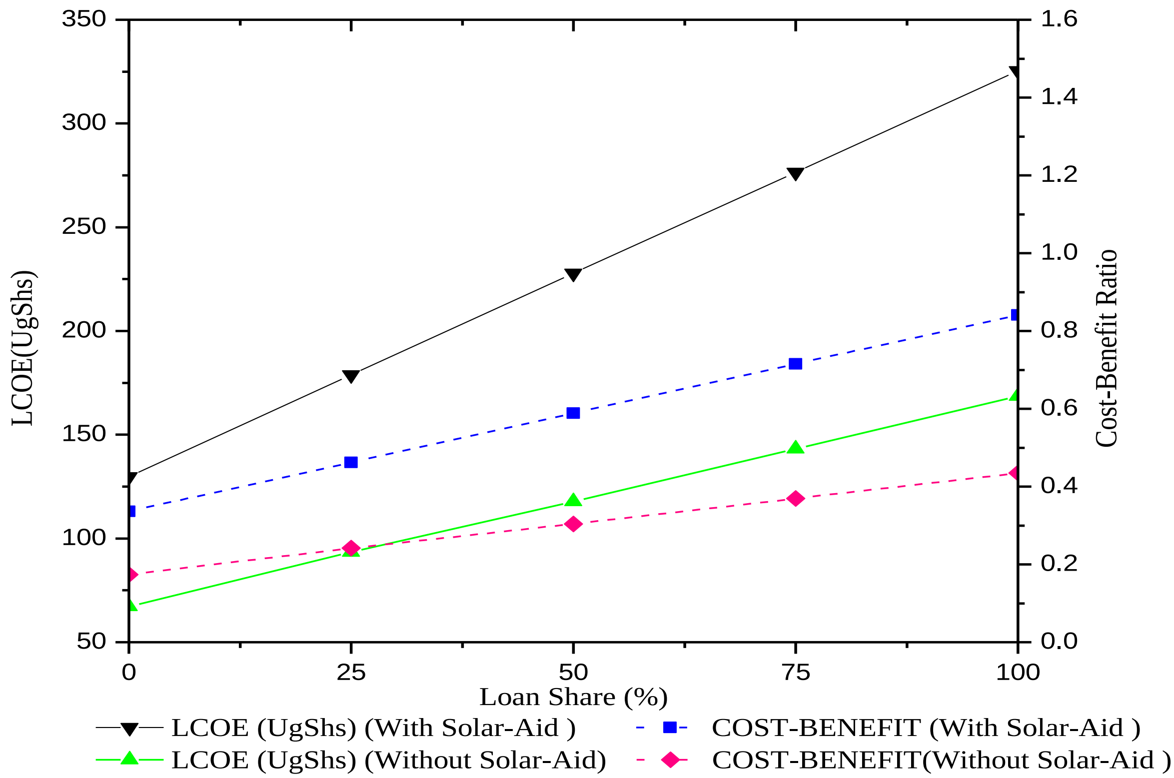



**Figure 5. 25: Effect of investment loan share to LCOE and Cost-Benefit Ratio of the systems**

From Figure 5. 25 above, it can be observed that the loan share percentage has an effect of the LCOE and Cost-Benefit Ratio of both systems. Both LCOE and Cost-Benefit Ratio increase for both systems as the loan share percentage on investment increases. Both digester systems are profitable even at 100 % loan share on investment.

The LCOE of the system was evaluated considering $\pm$ 10 % change in the investment costs due to the solar water heater costs and construction costs, daily cattle manure used and Hydraulic retention time (HRT). Their impact on the cost of a unit of energy produced from the system due to variation in a single variable was evaluated while other variables were maintained at the design specification values. Figure 5. 26 below shows the variation in LCOE with the different variables considered.

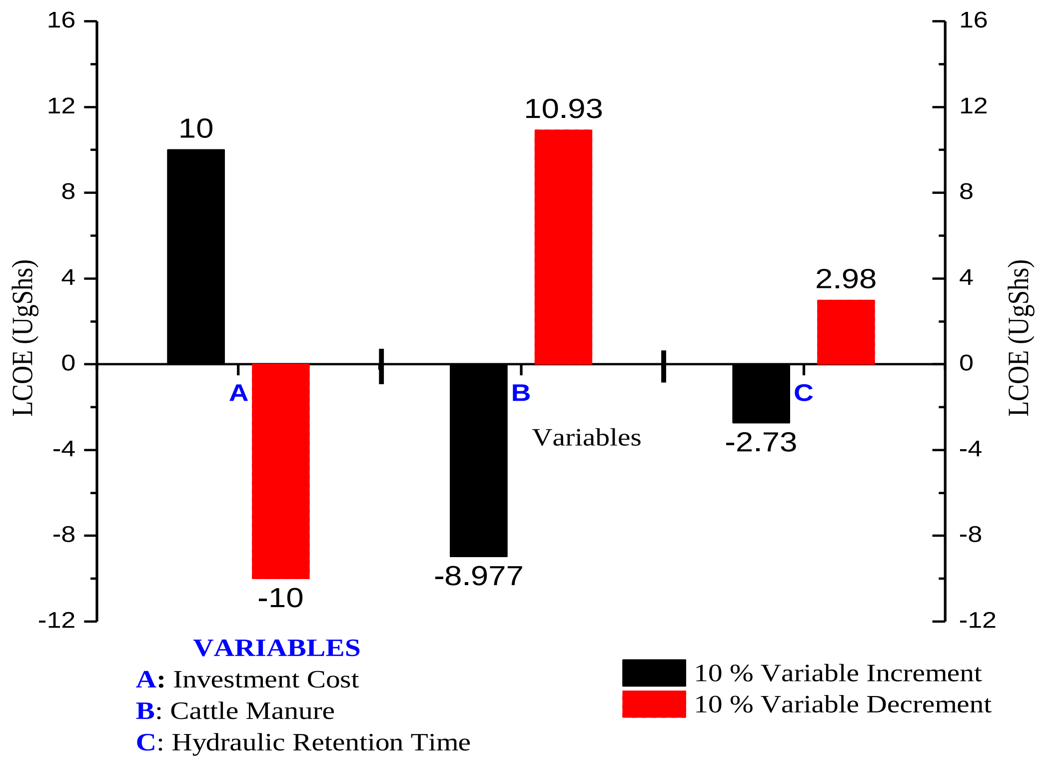



**Figure 5. 26: Sensitivity analysis of the designed system**

From Figure 5. 26 above, it can be observed that a change of ± 10 % in investment cost reflects respectively in the LCOE of the system as 10 % which is very influential on the investment execution. However, the change in daily cattle manure used shows different changes. An increase in cattle manure by 10 % (from 40 kg to 44 kg) results in a decrease of 8.98 % in the LCOE, this is because more volatile solids are introduced, thus increase in daily biogas production. On the other hand, a decrease in cattle manure by 10 % (from 40 kg to 36 kg) results in an increase of 10.93 % in the LCOE, this is because of the reduction in daily volatile solids introduced to the digester hence decrease in daily biogas production. The incremental change of 10 % in the hydraulic retention time shows a decrease of 2.73 % in the LCOE because the slurry in the digester is given more time to digest producing more biogas, and a decrease 10 % in the hydraulic retention time results in an increase of 2.98 % in the LCOE because the slurry in the digester has limited period of digesting thus egested while still productive with biodegradable volatile solids and thus low biogas production by the system.

The LCOE is more sensitive to decrease in daily cattle manure used, thus the manure should be maintained or increased to lower the LCOE of the system. The investment cost variation is directly reflected in the LCOE, thus, mechanisms of lowing the investment costs should be considered, that is, using locally fabricated glazed flat plate solar water heaters since they could be cheaper compared to the imported collectors.

## 5.9 Environmental Impact

A household was considered to constitute of 7 persons and on average having 3 meals necessitating about 1.00 $m^3$ of biogas per day to meet 75 % of all their cooking energy demands. By using biogas, the household would emit only 0.01 $kg_{CO_{2eq.}}$ per year avoiding GHG emissions of 4, 403.94 $kg_{CO_{2eq.}}$ per year, an equivalent of 99.9 % of emissions if firewood had been used for cooking and cattle manure left to digest in open space other than being used in the anaerobic digester. For anaerobic digester system of a lifetime of 30 years, the household would avoid emissions of 132.12 $T_{CO_{2eq.}}$ for this period of time. Further details on environmental impact assessment of this study are detailed in Appendix B-1. 7 of this report.

The digester effluent has only 36 % volatile solids per kilogram of the digester influent sludge, thus having minimal environmental impact compared to mere disposal of cattle manure without anaerobic digestion.

The effluent from the digester is rich in nutrients such as nitrogen and phosphorus and organic matter that can be used as a fertilizer in gardens. In addition, it has got minimal pathogen since most of them are destroyed by the thermophilic digester operating temperatures.

Utilization of biogas by the household saves the natural forests and woodlands that would have been degraded in search for firewood, since it reduces the firewood demand pressure on them, thus mitigating climate change.

# Chapter 6. CONCLUSION AND RECOMMENDATIONS

**Outline:**

## 6.0 Introduction

Energy accessibility and affordability is a key goal in the Sustainable Development Goals (SDG7), and its availability in rural areas is interlinked with other SDGs such as No Poverty (SDG1), Zero Hunger (SDG2), Good Health and Well-being (SDG3) and Climate Action (SDG13). This work was carried out with the main intention of availing clean energy to households and to curb the escalading deforestation in search for firewood in Uganda.

## 6.1 Conclusion

The aim of this study of designing, simulating and evaluating a solar-aided anaerobic digester system for small scale application in Uganda was accomplished. A 2.00 $m^3$ anaerobic digester system heated by circulating hot water from a 1.00 $m^3$ hot water tank heated by 11.75 $m^2$ solar water heater system was designed and simulated to evaluate the performance of the system in Kiruhura, Western Uganda based on the solar radiation received at the site as well as other climatic conditions such as ambient temperature. The digester was designed for a daily influent of 0.06 $m^3$ that resulted in hydraulic retention time of 27 days. The design daily influent had been determined from the initial assessment of the average number of cattle per household whose manure output would serve as the main feedstock of the digester. The necessary solar radiation and other weather data were obtained using Meteonorm version 7.1 software.

The simulated study digester model showed high correlation with experimental results. The coefficient of determination for methane production rate between experimental data and model data was 95.9 % while the coefficient of determination for cumulative methane yield between experimental data and model data was 99.8 % for the digester system simulated operating at 35.4 ℃ as it was carried out experimentally in the laboratory to generate the data sets.

At a daily influent of 0.06 $m^3$ and hydraulic retention time of 27 days, at an average digester temperature of 50 ℃, the designed system produces on average 2.22 $m^3$ of biogas per day, 2.4 times biogas production per day for a digester system operating at an average ambient temperature of 21 ℃ at the site. An amount that exceeds the anticipated daily biogas usage of 1 $m^3$ for a household of 7 persons preparing 3 meals daily. Thus a single designed system can be utilized by more than one household daily.

At a design hot water flow rate of 44 kg/h to the digester heating system, the designed anaerobic digester system was found to operate in temperatures ranging from 50 ℃ to 60 ℃ and only falling to about 47 ℃ during the worst irradiance-incident between May 28$^{th}$ to June 1$^{st}$ and November 14$^{th}$ to 18$^{th}$ at the site. The solar heating system delivers hot water in the temperature range of 50 ℃ to 67 ℃ throughout the year with the exception of the worst irradiance-incident period of the site. The hot water tank temperatures vary between 50 ℃ and 60 ℃, falling to about 43 ℃ during the worst irradiance-incident of the site. The anaerobic digester temperature on average takes 6 and 10 hours, respectively, during the best and worst irradiance-incident periods to vary by 1 ℃ , rendering favorable conditions for the microorganisms to adjust appropriately with the temperature variation. With the incorporation of the solar heating system to the digester system, the digester operates in the thermophilic temperature range (47 – 60 ℃) throughout the year at the study site.

With the use of biogas by a household to substitute 75 % of all its cooking energy demands, it avoids 4, 403.9 $\mathrm{kg_{CO_{2eq.}}}$ GHG emissions per year and an average of 1.17 $\mathrm{m^3}$ per year of firewood. Thus, firewood harvesting being one of the major causes of deforestation, usage of biogas for cooking energy demands would save the remnant forests and hence mitigate climate change. If the designed system is used by two households to utilize the excess biogas production per day, emissions of about 8, 807.9 $\mathrm{kg_{CO_{2eq.}}}$ GHG emissions per year could be avoided.

At the current bank interest rate on loans of 24.23 % in Uganda, the designed system is viable at any loan share percentage on investment cost because the system never reaches a break-even point at any loan share. Thus making the system profitable at all loan share percentages of investment cost of the system. Though the system is designed for household use, for purposes of maximum profits and minimizing costs, loan share percentages of less or equal 25% should be considered since they result in lower LCOE of the system, about 178.8 UgShs/kWh corresponding to about 46.2 % the Feed-in tariff of Uganda of 386.92 UgShs/kWh.

At a daily cattle manure requirement of 40 kg, the system can as well be sustained by a household in possession of at least 5 cattle, if it can collect at least 70 % of the total daily cattle manure produced. Since the designed system can meet energy demands for at least two households per day, it can be jointly implemented by two households for cases where each has less than 5 cattle.

The digester can as well accommodate any other organic material as feedstock keeping in mind the volatile solid concentration of daily feedstock to mitigate inhibitory of the microorganism activity and ease of pumping the influent to the digester.

The designed aboveground anaerobic digester system is advantageous over the underground anaerobic digester in case the household has got to shift to another location. The system is flexible for the household can carry it along with them to their new location if it was constructed on mount-support system aboveground.

## 6.2 Recommendations

Further investigation should be done on bleeding of hot water from the hot water tank to meet the warm water requirements of the households during the high irradiance-incident periods at the site since there are moments when the tank temperatures exceed 60 ℃.

Hot water mass flow rate to the digester heating system requires more investigation in order to be able to maintain the system at averagely 50 ℃ throughout the year. This accomplishment may as well result in reduction in Hot water tank size and solar collector area requirement for the system.

The designed solar-aided anaerobic digester system is quite expensive as discussed in chapter 5 because of the glazed flat plate solar water heater collectors used that are currently expensive in addition to costs of hot water tank construction and materials. Thus, further investigation should be done considering alternative solar water heaters to reduce the investment cost of the system.

Use of solar to heat anaerobic digester system on large scale application should be invested to assess the possibility of utilizing solar other than the other energy sources currently being used to heat the digester.

# REFERENCES

[1] United Nations (12 December 2015). "Adoption of the Paris Agreement." [Online]. Available: http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf. [Accessed 3 January 2016].

[2] Greenhouse Gas Protocol (2010). "GLobal Warming Potentials." [Online]. Available: http://www.ghgprotocol.org/files/ghgp/tools/Global-Warming-Potential-Values.pdf. [Accessed 5 May 2016].

[3] Ciotola R. J., Lansing S. and Martin J. F. (2011). "Emergy analysis of biogas production and electricity generation from small-scale agricultural digesters," *Ecological Engineering*, vol. 37, pp. 1681-1691.

[4] Jorgensen P. J. and PlanEnergi (2nd Ed.) (2009). "Biogas-Green Energy," Digisource Danmark A/S.

[5] Bond T. and Templeton M. R. (2011). "History and future of domestic biogas plants in the developing world," *Energy for Sustainable development*, vol. 15, pp. 347-354.

[6] Perrigault T., Weatherford V., Marti-Herrero J. and Poggio D. (2012). "Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model," *Bioresource Technology*, vol. 124, pp. 259-268.

[7] Yong Lu, Ye Tian, Haowei Lu, Lei Wu and Xianlin Li (2015). "Study of solar heated biogas fermentation system with a phase change thermal storage device," *Applied Thermal Engineering*, vol. 88, pp. 418-424.

[8] El-Mashad H. M., van Loon W. K. P., Zeema G., Bot G. P. A and Lettinga G. (2004). "Design of a solar thermophilic anaerobic reactor for small farms," *Biosystems Engiineering,* vol. 87, no. 3, pp. 345-353.

[9] El-Mashad H. M., van Loon W. K. P. and Zeeman G. (2003). "A model of solar energy utilisation in the anaerobic digestion of cattle manure," *Biosystems Engineering,* vol. 84, no. 2, pp. 231-238.

[10] Feiqing Dong and Jianbo Lu (2013). "Using solar energy to enhance biogas production from livestock residue- A case study of the Tongren biogas engineering pig farm in South China," *energy,* vol. 57, pp. 759-765.

[11] Kumar K. V. and Bai R. K (2008). "Solar greenhouse assistd biogas plant in hilly region- A field study," *Solar Energy,* vol. 82, pp. 911-917.

[12] Uganda Bureau of Statistics (2014). "Uganda Rural-Urban Electrification Survey, 2012," Ministry of Energy and Mineral Development, Kampala.

[13] Kisawuzi Ian (2015). "Household Energy surveys in Uganda," Ministry of Energy and Mineral Development, Kampala.

[14] Uganda Bureau of Statistics (2014). "2014 Statistical Abstract," Uganda Bureau of Statistics, Kampala.

[15] Charcoalproject (18 November 2009). "Uganda will need to import firewood in 2020," Charchoalproject. [Online]. Available: http://www.charcoalproject.org/2009/11/uganda-will-need-to-import-firewood-in-2020/. [Accessed 16 June 2016].

[16] Ministry of Energy and Mineral Development (2002). "The Energy Policy for Uganda," Ministry of Energy and Mineral Development, Kampala.

[17] Karume K., Banda E. J. K. B., Mubiru J. and Majaliwa M. (2007). "Correlation between sunshine hours and climatic parameters at four locations in Uganda," *Tanzania Journal of Science,* vol. 33, pp. 93-100.

[18] Institute for Security Studies Africa (2014). "Uganda - Ecomony," Institute for Security Studies Africa. [Online]. Available: https://www.issafrica.org/AF/profiles/Uganda/Economy.html. [Accessed 5 May 2016].

[19] Uganda Bureau of Statistics (2010). "The National Livestock Census Report 2008," Ministry of Agriculture, Animal Industry & Fisheries, Kampala.

[20] Caslin Barry (22 October 2009). "Potential of Farm Scale AD in Ireland," Sustainable Energy Authority of Ireland. [Online]. Available: https://www.seai.ie/Renewables/AD_In_Ireland_22nd_October/Potential_of_Farm_Scale_AD_in_Ireland.pdf. [Accessed 25 April 2016].

[21] Natural Resources Conservation Service (7 December 1995). "Animal Manure Management," United Nations Department of Agriculture. [Online]. Available: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/nj/technical/cp/cta/?cid=nrcs143_014211. [Accessed 26 April 2016].

[22] EPA (2005). "Anaerobic Digestion: Benefits for Waste Management, Agriculture, Energy, and," Environmental Protection Agency of Ireland,Wexford , Ireland.

[23] IPCC (2007a). "Summary for Policymakers. Climate Change 2007: Mitigation," Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University, Cambridge, UK and New York, USA.

[24] Schön Michael (2007). "Numerical modelling of anaerobic digestion processes in agricultural biogas plants. PhD dissertation,," Innserbuck University, Austria.

[25] de Mes T.Z.D., Stams A. J. M., Reith J. H. and Zeeman G. (2003). "Methane production by anaerobic digestion of wastewater and solid wastes." In: Reith J. H., Wiiffels R. H. & Barten H. (editors) (2003)."Biomethane and Biohydrogen Status and perspectives of biological methane and hydrogen production," pp. 58-94.

[26] Pavlostathis S. G. and Giraldo-Gomez E. (1991). " Kinetics of anaerobic treatment: a critical review," *Critical Reviews in Environmental Control,* Vols. 21 (5,6), pp. 411-490.

[27] Boe Kanokwan (2006). "Online monitoring and control of the biogas process. PhD Thesis," Institute of Environment & Resources, Technical University of Denmark, Lyngby, Denmark.

[28] Gujer W. and Zehnder A. J. B. (1983). " Conversion processes in anaerobic digestion," *Water Science and Technology,* vol. 15, pp. 127-167.

[29] Suryawanshi P. C., Chaudhari A. B., Bhardwaj S. and Yeole T. Y. (2013). "Operating Procedures for Efficient Anaerobic Digester Operation," *Research Journal of Animal, Veterinary and Fishery Sciences,* vol. 1, no. 2, pp. 12-15.

[30] Sanju Nanda (2008). "Pharmaceutical Engineering: Reactor and Fundamentals of Reactors Design for Chemical Reaction," Department of Pharmaceutical Sciences, M. D. University, Delhi.

[31] Rittmann B. E. and McCarty P. L. (2001). "Environmental biotechnology: Principles and applications (International ed.)," McGraw Hill, Singapore.

[32] Turovskiy Izrail S. and Mathai P. K. (2006). "Waste Water Sludge Processing," A John Wiley & Sons, Inc., New Jersey.

[33] Bio-gas project & LGED (2009). "Design of Biogas Plant." [Online]. Available: http://www.sswm.info/sites/default/files/reference_attachments/BRC%20ny%20Design%20Biogas%20Plant.pdf. [Accessed 19 April 2016].

[34] Lettinga G. and van Haandel A. C. (1993). "Anaerobic digestion for energy production and environmental protection." In: Renewable Energy Sources for Fuels and Electricity, J. T. B. e. al., Ed., Washington DC: Island Press, pp. 817-839.

[35] Buysman E. (2009). "Anaerobic Digestion for Developing Countries with Cold Climates - Utilizing solar heat to address technical challenges and facilitating dissemination through the use of carbon finance. Master Thesis.," University of Wageningen, Wageningen.

[36] Marco von Sperling and Carlos Augusto de Lemos Chernicharo (2006). "Biological Wastewater Treatment in Warm Climate Regions," vol. 1, London: IWA Publishing, pp. 320-340.

[37] Ruggeri Bernardo, Tommasi Tonia and Sanfilippo Sara (2015). "BioH2 & BioCH4 Through Anaerobic Digestion: From Research to Full-scale Applications," London: Springer-Verlag London Ltd., pp. 92-96.

[38] Osman A. Arikan, Walter Mulbry and Stephanie Lansing (2015). "Effect of temperature on methan production from field-scale anaerobic digesters treating dairy manure," *Waste Management,* vol. 43, pp. 108-113.

[39] Bandara W. M. K., Kindaichi T., Satoh H., Sasahawa M. and Nakahara Y. (2012). "Anaerobic treatment of municipal wastewater at ambient temperature: Analysis of archaeal community structure and recovery of dissolved methane," *Water Research,* vol. 46, pp. 5756-5764.

[40] Przywara L., Mrowiec B. and Suschka J. (2011). "Municipal sewage treatment in upflow anaerobic filter," University of Bielsko-Biala, Bielsko-Biala.

[41] Philip T. K. and Itodo I. N. (2007). "Nomograph for determining temperatures in anaerobic digesters from ambient temperatures in the tropics," *Agricultural Engineering International: the CIGR Ejournal,* vol. 9, pp. 006-010.

[42] Lutaaya Fred (2013). "Quality and usage of biogas digesters in Uganda," Royal Institute of Technology, Stockholm, Sweden.

[43] Ravoof A. A., Fox R. F. and Sanford W. G., "Illustrated concepts in tropical agriculture," University of Hawaii, Hawaii, 1973.

[44] William Davis Mace (2012). "Master Thesis: Environmental differences in tropical soil temperatures in Kenya," The University of Utah, Utah.

[45] Gray N. F. (2004). "Biology of wastewater treatment. 2nd edition," Imperial College Press, Londan.

[46] Eder B. and Schulz H. (2006). "Biogas Praxis [in German], 3rd Edition," ökobuch Verlag, Staufen, Germany.

[47] Wellinger Arthur, Murphy Jerry and Baxter David (2013). "The Biogas Handbook: Science, Production and Applications," Philadelphia: Woodhead Publishing Limited, pp. 134-140.

[48] Grady C. P. L., Daigger G. T. and Lim H. C. (1999). " Biological Wastewater Treatment. 2nd Edition," Marcel Dekker Inc., New York.

[49] Tchobanoglous G., Burton F. L. and Stensel H. D. (2003). "Wastewater Engineering: Treatment and Reuse, 4th Edition," Metcalf & Eddy, Inc., Tata McGraw-Hill Publishing Company Ltd.

[50] Steffen R., Szolar O. and Braun R. (1998). "Feedstocks for Anaerobic Digestion," Institute for Agrobiotechnology Tulln, University of Agricultural Sciences Vienna.

[51] Haug T. R. (1993). The practical handbook of compost engineering, CRC.

[52] Zeeman G., "Discussion on biogas generation," Wageningen, 2008.

[53] GTZ (1989). "Biogas plant in Animal Husbandry, Deutshe Zentrum fur Entwicklungstechnologien - GATE."

[54] Dennis A. and Burke P.E. (2001). "Dairy Waste Anaerobic Digestion Handbook," Environmental Energy Company, Olympia.

[55] Prakash Parajuli (2011). "Master Thesis: Biogas measurement techniques and the associated errors," University of Jyväskylä, Jyväskylä.

[56] Nijaguna B. T. (2002). "Biogas Technology," *New Age International*, pp. 46-48.

[57] Charles Banks (2011). *Anaerobic digestion and energy*, University of Southampton.

[58] Hashimoto A. G. (1984). "Methane from swine manure: Effect of temperature and influent substrate concentration on kinetic parameter (K)," *Agric. Wastes*, vol. 9, pp. 299-308.

[59] AgSTAR Program (2003). "Industry Directory for On-Farm Biogas Recovery Systems," 2nd ed., Florida: BioCycle Magazine , pp. 48-52.

[60] Axaopoulos P., Panagakist P., Tsavdaris A. and Georgakakis D. (2001). "Simulation and experimental performance of a solar-heated anaerobic digester," *Solar Energy*, vol. 70, no. 2, pp. 155-164.

[61] Hill D. T. (1982b). "Design of digestion systems for maximum methane production," *Transactions of the ASAE*, vol. 25, pp. 227-230,236.

[62] Chen Y. and Hashimoto R. (1978). "Kinetics of methane fermentation. Proceedings of Symposium on Biotechnology in Energy Production and Conservation," Scott C. D (Ed.), John Wiley, New York.

[63] Hashimoto A. G, Chen Y. R., and Varel V. H. (1981). "Theoretical aspects of methane production: state- of-the-art. In Livestock Wastes: A Renewable Resource," no. MI.

[64] Rapport Joshua, Zhang Ruihong, Jenkins Bryan M. and Williams Robert B. (2008). "Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste," California Environmental Protection Agency, California.

[65] Nielfa A., Cano R. and Fdz-Polanco M. (2015). "Theoretical methane production generated by the co-digestion of organic fraction municipal solid waste and biological sludge," *Biotechnology Reports,* vol. 5, pp. 14-21.

[66] Contreras Edgardo M., Bertola Nora C., Giannuzzi Leda and Zaritzky Noemi E. (2002). "A modified method to determine biomass concentration as COD in pure cultures and in activated sludge systems," *Water,* vol. 28, no. 4, pp. 463-468..

[67] Van Haandel A. C. and Van der Lubbe J. G. M. (2012). "Handbook of Biological Wastewater Treatment: Design and Optimisation of Activated Sludge Systems," 2nd ed., London: IWAPublishing.

[68] Zhenjie R., Zhili C., Li-an H., Wenbiao W., Kaisheng X., Xiao X. and Wantu Z. (2012). "Design investigation of a solar energy heating system for anaerobic sewage treatment," *Energy Procedia,* vol. 14, pp. 255-259.

[69] Yiannopoulos A. C., Manariotis I. D. and Chrysikopoulos C. V. (2008). "Design and analysis of a solar reactor for anaerobic wastewater treatment," *Bioresource Technology,* vol. 99, pp. 7742-7749.

[70] El-Mashad H. M. W. K. P., van Loon, et al. (2004). "Design of A solar Thermophilic Anaerobic Reactor for Small Farms," *Biosystems Engineering,* vol. 87, no. 3, pp. 345-353.

[71] Bergman Theodore L., Lavine Adrienne S., Incropera Frank P. and Dewitt David P. (2011). "Fundamentals of Heat and Mass Transfer," 7th ed., Jefferson City: John Willey & Sons, pp. 539-550.

[72] Rod Nave (2015). "Thermodynamics," HyperPhysics-Geerogia state University. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/vappre.html. [Accessed 17 May 2016].

[73] Gauché Paul (2012). "Solar thermal energy systems pre-reader for 2012," 1st ed., Stellenbosch: Stellenbosch University.

[74] David Darling (2014). "solar collector," [Online]. Available: http://www.daviddarling.info/encyclopedia/S/AE_solar_collector.html. [Accessed 23 April 2016].

[75] Anita516 (2016). "Brief Introduction to the Flat Plate Solar Collector Riser Tubes." [Online]. Available: http://www.shoptsie.com/anita516/product/388-brief-introduction-to-the-flat-plate-solar-collector-riser-tubes/. [Accessed 23 April 2016].

[76] Intelligent Energy (2012). "Energy-Solar Collectors." [Online]. Available: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/solco_training_solar_collectors_en.pdf. [Accessed 23 April 2016].

[77] Academic Press (2009). "Renewable Energy Focus Handbook," New York: Elsevier Inc., pp. 364-375.

[78] SOLTRAIN (2009). "Thermal Use of Solar Energy," AEE - Institute for Sustainable Technologies, Austria.

[79] Duffie John A. and Beckman William A. (2013). "Solar Engineering of Thermal Processes," 4th ed., New JErsey: John Wiley & Sons. Inc.

[80] Weiss Werner (2014). "Solar Collector," AEE - Institute for Sustainable Technologies (AEE INTEC), AUSTRIA.

[81] Struckmann Fabio (2008). "Analysis of a Flat-plate Solar Collector," Lund University, Lund, Sweden.

[82] Peter Kovacs (2012). "Quality Assurance in Solar Heating and Cooling Technology: A Guide to the Standard EN 12975," Science Partner – Technical Research Institute of Sweden, Sweden.

[83] Weiss Werner (2014) "Solar Radiation," AEE-Institute for Sustainable Technologies (AEE INTEC), Austria.

[84] The Engineering ToolBox (2014). "Ethylene Glycol Heat_Transfer Fluid," The Engineering ToolBox. [Online]. Available: http://www.engineeringtoolbox.com/ethylene-glycol-d_146.html. [Accessed 10 May 2016].

[85] Çengel Yunus A. and Boles Michael A. (2015). "Thermodynamic: An Engineering Approach," 8th ed., New York: Mc Gra Hill Education, pp. 232-370.

[86] Çengel Yunus A. adn Ghajar Afshin J. (2015). "Heat and Mass Transfer: Fundamentals & Applications," 5th ed., Singapore: McGraw-Hill Education, pp. 432-448.

[87] Balat B. K and Hossain M. M. (1992). "Economics of Biogas Digesters in Bangladesh," *Energy* , vol. 17, no. 10, pp. 939-944.

[88] Kost Christoph, Mayer Johannes N., Thomsen Jessica, Hartmann Niklas, Senkpiel Charlotte, Philipps Simon, Nold Sebastian, Lude Simon, Saad Noha and Schlegl Thomas (2013). "Levelized Cost of Electricity Renewable Energy Technologies," Rainer Sturm 2010, Freiburg.

[89] Clementson Margareta and BioWrite Jarvis (2007). "Biogas: Basic Data on Biogas," Sweden Gas Centre, Sweden.

[90] IRENA (2012). "Renewable Energy Technologies: Cost Analysis Series- Biomas for Power Generation," Internation Renewable Energy Agency, Bonn.

[91] Garfi Marianna, Ferrer-Marti Laia, Velo Enrique and Ferrer Ivet (2011). "Evaluating benefits of low-cost household digesters for rural Andean communities," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 575-581.

[92] US Environmental Protection Agency (4 April 2014). "Emission Factors for Greenhouse Gas Inventories," US Environmental Protection Agency. [Online]. Available: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf. [Accessed 12 June 2016].

[93] Dong Hongmin, Mangino Joe and McAllister Tim A. (2006). " Chapter 10: Emissions from Livestock and Manure Management," Intergovernmental Panel on Climate Change. [Online]. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf. [Accessed 12 June 2016].

[94] Agea Jacob Godfrey, Kirangwa Denis, Waiswa Daniel and Okia Clement Akais (2010). "Household Firewood Consumption and its Dynamics in Kalisizo Sub-County, Central Uganda," *Ethnobotanical Leaflets*, vol. 14, pp. 841-855.

[95] Gavin Brock and Box Hill (February 2004). "Properties of firewood." [Online]. Available: http://www.thegreenyard.com.au/wp-content/uploads/2015/05/Firewood-Properties1.pdf. [Accessed 10 June 2016].

[96] Agama Biogas (2010). "BiogasPro Product Datasheet," AGAMA Biogas (Pty) Ltd, Cape Town.

[97] Prakash Thapa (2012). "Master Thesis: Anaerobic Conversion of Glycol Rich Industrial WAstewater to Biogas," University of Stavaanger, Stavanger, Norway.

[98] Klein S. A. (2003). "EES: Engineering Equation Solver for Microsoft Windows Operating Systems," F-Chart Software, Middleton.

[99] Blair Nate, Dobos Aron P., Freeman Janine, Neises Ty and Wagner Michael (2014). "System Advisor Model, SAM 2014.1.14: Genral Description." [Online]. Available: http://www.nrel.gov/docs/fy14osti/61019.pdf. [Accessed 8 6 2016].

[100] Chukwubuikem Chukwuka K. F. (2015). "An Economic Assessment of the Concentrated Solar Power with National Energy Regulator of South African Feed-in Tariff Scheme," *Journal of Energy and Power Sources*, pp. 137-143.

[101] Jan Remund, Stefan Müller, Stefan Kunz, Barbara Huguenin-Landl, Christian Studer, Daniel Klauser, Christoph Schilter and Reto Lehnherr (2016). "Haandbook Part 1: Software Version 7.1," Meteotest, Bern.

[102] Jan Remaud and Stefan Muller (2011). "Solar Radiation and Uncertainty Information of Meteonorm 7," Meteotest, Bern.

[103] Public Procurement and Disposal of Public Assets Authority (November 2014). "List of common user items and their average prices," Public Procurement and Disposal of Public Assets Authority. [Online]. Available: https://ppda.go.ug/download/downloads/corporate_reports/PPDA%20List%20of%20Common%20User%20Items_Dec2014.pdf. [Accessed 10 June 2016].

[104] Uganda Bureau of Statistics (June 2016). "Statistics," Bank of Uganda. [Online]. Available: https://www.bou.or.ug/bou/rates_statistics/statistics.html. [Accessed 22 June 2016].

[105] Electricity Regulatory Authority (2012). "Uganda Renewable Energy Feed-in Tariff (REFIT)," Electricity Regulatory Authority, Kampala.

# GLOSSARY

| | |
|---|---|
| BOD | Biological oxygen demand, biochemical oxygen demand: is the oxygen consumed by aerobic microorganisms to degrade organic matter in the effluent. |
| BOD5 | Five-day biological oxygen demand |
| COD | Chemical oxygen demand: is a measure of the amount of oxygen consumed as a result of chemical oxidation of the organic matter. COD and BOD differ in the nomenclature of both tests, BOD relates itself with the biochemical oxidation of the organic matter undertaken entirely by microorganisms while COD corresponds to the chemical oxidation of the organic matter obtained through a strong oxidant (Potassium dichromate) in an acid medium. |
| Composting | Is the microbiological degradation of organic material to humus like stable product under aerobic, moist and self-heating conditions. |
| Dry Digestion | Total solids content of the waste concentrations can be as high as 35%. |
| EPW | Energy Plus Weather data |
| GHG | Green House Gas |
| High-rate anaerobic | short hydraulic retention time (usually less than 1 day) and high organic loading rate. |
| High-solid wastes | organic material with a content of solids between 10 to 40%, which is not fluid |
| HRT | Hydraulic Retention Time: is equal to the volume of sludge in the digester ($m^3$) divided by the volume of digested sludge withdrawn daily (m3 /d). |
| IPCC | Intergovernmental Panel on Climate Change |
| IPPC | Integrated Pollution Prevention and Control |

| | |
|---|---|
| SRCC | Solar Rating and Certification Corporation |
| SRT | Solid Retention Time: is equal to the mass of solids in the digester (kg) divided by the mass of solids withdrawn daily (kg/d). such as Municipal Solid Waste (MSW) or Household Solid Waste (HSW) |
| TMY | Typical Metrological Year |
| Wet Digestion | Total solids content of the waste has to be reduced to concentrations below 20% in order to create a pumpable slurry. |
| Total Solids | Summation of organic and inorganic solids in a substrate. They are subdivided into suspended and dissolved solids and settleable solids. Depended when a substrate is subjected to a temperature of 105 ℃. |
| Suspended solids | Part of organic and inorganic solids that are non-filterable. They are also subdivided into fixed and volatile solids. |
| Dissolved solids | Part of organic and inorganic solids that filterable, normally considered having a dimension less than $10^{-3}\mu m$ they are also subdivided into fixed and volatile solids. |
| Fixed solids | Mineral compounds not oxidized by heat, inert, which are part of the suspended/dissolved solids. |
| Volatile solids | Organic compounds, oxidized by heat, which are part of the suspended/dissolved solids. They oxidize when the substrate is subjected to higher temperature (550 ℃) |
| Settleable solids | Part of organic and inorganic solids that settle in 1 hour in an Imhoff cone. Approximate indication of the settling in a sedimentation tank. |

# APPENDICES

## Appendix A

### A-1. 1: Glazed Flat Plate solar water heater collector Catalogue

Alternate Energy Technologies • AE-26

| SOLAR COLLECTOR CERTIFICATION AND RATING | CERTIFIED SOLAR COLLECTOR |
|---|---|
| SRCC OG-100 | SUPPLIER: **Alternate Energy Technologies**<br>1057 N. Ellis Road<br>Jacksonville, FL 32254<br><br>MODEL: Alternate Energy AE-26<br>COLLECTOR TYPE: Glazed Flat-Plate<br>CERTIFICATION #: 100-2002-001C |

**COLLECTOR THERMAL PERFORMANCE RATING**

| Megajoules Per Panel Per Day | | | | Thousands of Btu Per Panel Per Day | | | |
|---|---|---|---|---|---|---|---|
| CATEGORY (Ti-Ta) | CLEAR DAY 23 MJ/m²·d | MILDLY CLOUDY 17 MJ/m²·d | CLOUDY DAY 11 MJ/m²·d | CATEGORY (Ti-Ta) | CLEAR DAY 2000 Btu/ft²·d | MILDLY CLOUDY 1500 Btu/ft²·d | CLOUDY DAY 1000 Btu/ft²·d |
| A (-5°C) | 35 | 26 | 18 | A (-9°F) | 33 | 25 | 17 |
| B (5°C) | 32 | 23 | 15 | B (9°F) | 30 | 22 | 14 |
| C (20°C) | 27 | 18 | 10 | C (36°F) | 25 | 17 | 9 |
| D (50°C) | 16 | 8 | 2 | D (90°F) | 15 | 8 | 2 |
| E (80°C) | 6 | 1 | | E (144°F) | 6 | 1 | |

A-Pool Heating (Warm Climate) B-Pool Heating (Cool Climate) C-Water Heating (Warm Climate) D-Water Heating (Cool Climate) E-Air Conditioning

Original Certification Date: November 22, 2002

**COLLECTOR SPECIFICATIONS**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gross Area:** | 2.355 | m² | 25.35 | ft² | | **Net Aperture Area:** | 2.197 | m² | 23.65 | ft² |
| **Dry Weight:** | 40.8 | kg | 90 | lb | | **Fluid Capacity:** | 3.8 | l | 1.0 | gal |
| **Test Pressure:** | 1103 | kPa | 160 | psig | | **Max. Oper. Temp.:** | 176.7 | °C | 350 | °F |

**COLLECTOR MATERIALS**

| | |
|---|---|
| **Frame:** | Anodized Aluminum |
| **Cover (Outer):** | Low Iron Tempered Glass |
| **Cover (Inner):** | None |
| **Absorber Material:** | Tube - Copper / Plate - Copper Fin |
| **Absorber Coating:** | Selective Coating |
| **Insulation (Side):** | Polyisocyanurate |
| **Insulation (Back):** | Polyisocyanurate |

**PRESSURE DROP**

| Flow | | ΔP | |
|---|---|---|---|
| ml/s | gpm | Pa | in $H_2O$ |
| | | | |

**TECHNICAL INFORMATION**

**Efficiency Equation [NOTE: (P) = Ti-Ta]**

| | | | | | | Y Intercept | Slope | |
|---|---|---|---|---|---|---|---|---|
| **S I Units:** | $\eta$ = 0.691 | -3.3960 | (P)/I | -0.0019 | $(P)^2/I$ | 0.706 | -4.9099 | W/m²·°C |
| **I P Units:** | $\eta$ = 0.691 | -0.5985 | (P)/I | -0.0002 | $(P)^2/I$ | 0.706 | -0.865 | Btu/hr·ft²·°F |

**Incident Angle Modifier [(S) = 1/cos θ - 1, 0°≤θ≤60°]**

$K_{\alpha\tau}$ = 1.0 -0.1939 (S) -0.0055 $(S)^2$
$K_{\alpha\tau}$ = 1.0 -0.20 (S) (Linear Fit)

**Model Tested:** AE-21
**Test Fluid:** Water
**Test Flow Rate:** 39 ml/s 0.62 gpm

**REMARKS:**

October, 2004
Certification must be renewed annually. For current status contact:
SOLAR RATING & CERTIFICATION CORPORATION
c/o FSEC • 1679 Clearlake Road • Cocoa, FL 32922 • (321) 638-1537 • Fax (321) 638-1010

# Appendix B

## B-1. 1: Anaerobic Digester System

The digester system was subdivided into two categories of dimensioning; digester dimensions and digester heating system dimensions. These two subdivisions are detailed in the tables below under their respective heading.

### B-1.1.1: Digester dimensions

The digester was scaled based on the guidelines detailed in literature view sub section 2.3.3.1 and the table below shows the respective values that were attained.

| **Dimension** | **Value** | **Description** |
|---|---|---|
| $V_{dig}$ $(m^3)$ | 2.0 | Digester volume |
| $V_c$ $(m^3)$ | 0.1 | Gas collecting volume |
| $V_s$ $(m^3)$ | 0.3 | Slurry layer volume |
| $V_w$ $(m^3)$ | 1.6 | Working volume |
| $V_{gs}$ $(m^3)$ | 0.2901 | Gas storage volume |
| $V_f$ $(m^3)$ | 1.31 | Fermentation slurry volume |
| $V_r$ $(m^3)$ | 1.61 | Reactor volume |
| $D_{dig}$ $(m)$ | 1.241 | Digester diameter |
| $H_{dig}$ $(m)$ | 1.654 | Digester height |
| Area $(m^2)$ | 4.625 | Digester surface area |
| Stainless steel $(m)$ | $2.5 \times 10^{-3}$ | Digester structure |
| Extended polystyrene $(m)$ | 0.1 | Digester insulation |
| Concrete $(m)$ | 0.2 | Digester insulation |
| Rate of heat loss (W/$^{o}$C) | 0.37 | Rate of Heat loss from the digester |

### B-1.1.2: Digester Heating system

From the heat energy requirement of the digester to operate in the thermophilic temperature zone, mainly between 50 $°C$ and 60 $°C$, the table below shows the details of the copper pipe heating system of the digester.

| Entry | Value | Description |
|---|---|---|
| $D_{pipe}$ $(m)$ | 0.018 | Inner diameter of the copper pipe |
| $b_{pipe}$ $(m)$ | 0.002 | Thickness of the copper pipe |
| $D_{dig}$ $(m)$ | 1.241 | Digester diameter |
| N $(loops)$ | 8 | Number of loops of copper pipe in the digester |
| $L_{pipe}$ $(m)$ | 31.17 | Length of copper pipe coiled in the digester |
| $T_{in}$ $(°C)$ | 60 | Inlet water temperature to the digester heating system |
| $T_{dig}$ $(°C)$ | 50 | Digester operating temperature |
| $T_{pipe}$ $(°C)$ at ($T_{in} = 60°C$ & $T_{dig} = 50°C$) | 55 | Pipe temperature inside the digester. Considered as the average between the inlet water and digester operating temperature |
| $\dot{m}_{dig}$ $(kg/s)$ | 0.01223 | Hot water mass flow to the digester heating system |

### B-1. 2: Digester Feedstock

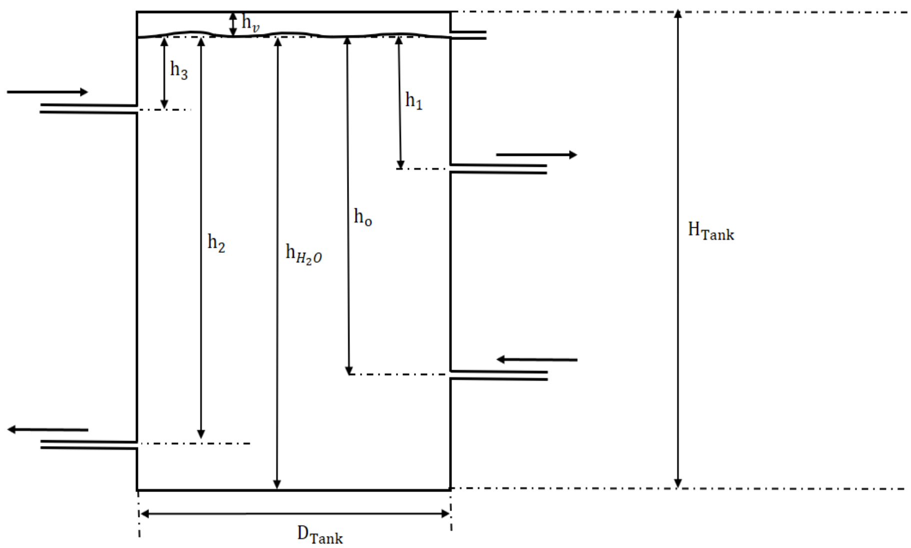
The main substrate considered in this study is the cattle manure because of its abundance at the study site. The table shows the details of the feedstock and production of gas from the anaerobic digester operating at $50\ °C$.

### B-1.2.1: Substrate details and Gas production of the digester

| Entry | Value | Description |
|---|---|---|
| Cattle manure (kg/day) | 40 | Manure to be used daily |
| Dilution water (kg/day) | 20 | Water to dilute the manure daily |
| Daily influent $(m^3/day)$ | 0.06 | Daily slurry fed to the digester |
| Volatile solids $(kg\ VS/m^3\ V_r\ day)$ | 2.5534 | Total volatile solids introduced to the digester daily |
| Total Solid content (%) | 12 | Solid content in every kg of cattle manure |
| Desired solid content (%) | 8 | Intended solid concentration of daily influent |
| HRT (days) | 27 | Hydraulic retention time of the slurry |
| $T_{dig}$ $(°C)$ | 50 | Digester operating temperature |
| $\mu_m$ $(day^{-1})$ at 50 $°C$ | 0.521 | Maximum specific growth rate of microorganisms |
| $\beta_o$ $(m^3\ CH_4/kg\ VS)$ at 50 $°C$ | 0.4138 | Ultimate methane yield of the substrate |
| $K$ at 50 ° | 0.8186 | Kinetic parameter of the anaerobic process |
| $Y$ $(m^3\ CH_4)$ at 50 $°C$ for 27 days | 36.015 | Cumulative methane yield by the digester |
| $\kappa$ $(m^3\ biogas)$ at 50 $°C$ for 27 days | 60.025 | Cumulative Biogas yield considering 60% of biogas being methane |
| $\mu$ $(m^3\ biogas)$ at 50 $°C$ | 2.223 | Average biogas production rate of the digester |

### B-1. 3: Hot Water Storage Tank

To ensure effectiveness of the system and natural convection with on the tank, the outlet and inlet pipes were designed to respective positions of the tank effect the pressure of the flows to and from the digester heating system and the solar collector system. Figure below shows the schematics of the designed storage tank for this study.




The values to the respective heights denote by $h$ in Figure are above are shown in the table below.

| **Dimension** | **Value (m)** | **Description** |
|---|---|---|
| $h_o$ | 0.983 | Height between the top level of water in the tank and the inlet pipe from the digester heating system |
| $h_1$ | 0.453 | Height between the top level of water in the tank and the outlet pipe to the digester heating system |
| $h_2$ | 1.183 | Height between the top level of water in the tank and the outlet pipe to the solar collector system |
| $h_3$ | 0.2 | Height between the top level of water in the tank and the inlet pipe from the solar collector system |
| $h_o - h_1$ | 0.43 | Height between the inlet and outlet to the digester heating system |
| $h_2 - h_3$ | 0.983 | Height between inlet and outlet to solar collector system |
| $h_{H_2O}$ | 1.383 | Height from the bottom of the tank to the top level of water in the tank |
| $H_{Tank}$ | 1.483 | Height of the water tank |
| $D_{Tank}$ | 0.9269 | Diameter of the water tank |
| $h_v$ | 0.1 | Height of the vapor space in the tank |
| $V_{Tank}$ | 1.001 | Volume of the water tank |
| Area | 5.6686 | Surface area of the water tank |

## B-1. 4: Solar Collector System

Glazed flat plate water heating solar collector type AE-26 of SRCC 2002001C 2 was used in this study and the table below shows the details used in setting up the solar collector system of the study.

### B-1.4.1: Solar collector system details of the study

| Dimension | Value | Description |
|---|---|---|
| $A_{coll}$ $(m^2)$ | 2.35 | Gross Area of each collector |
| Tilt angle (°) | 15 | Elevation angle from the ground |
| Azimuth (°) | 0 | Orientation to south direction |
| N | 5 | Number collectors used |
| $T_{in}$ | 51 | Average Inlet water temperature to the collector system |
| IAM | 0.19 | Incident Angle Modifier |
| $\eta_o$ | 0.691 | Nominal efficiency of a collector |
| $\dot{m}_{coll}$ | 0.05282 | Mass flow of water to the collector system |

## B-1. 5: System Heat Loss evaluation

| Entry | Value | Description |
|---|---|---|
| $k_{steel}$ $(W/m\,K)$ | 14 | Thermal conductivity of stainless steel |
| $k_{polystyrene}$ $(W/m\,K)$ | 0.032 | Thermal conductivity of polystyrene |
| $k_{concrete}$ $(W/m\,K)$ | 0.7 | Thermal conductivity of concrete |
| $h_{i,water}$ $(W/m^2\,K)$ | 0.1205 | Heat transfer coefficient of water (at 60 ℃) |
| $h_{i,slurry}$ $(W/m^2\,K)$ | 0.1126 | Heat transfer coefficient of slurry (at 50 ℃) |
| $h_o$ $(W/m^2\,K)$ | 5.52 | Heat transfer coefficient of air (at 25 ℃ & 3 m/s) |
| $b_{steel}$ $(m)$ | $2.5 \times 10^{-3}$ | Thickness of stainless wall |
| $b_{polystyrene}$ $(m)$ | 0.1 | Thickness of polystyrene wall |
| $b_{concrete}$ $(m)$ | 0.2 | Thickness of concrete wall |
| $R_{tot,digester}$ $(m^2\,K/W)$ | 12.474 | Total heat transfer resistance of the digester wall |
| $R_{tot,tank}$ $(m^2\,K/W)$ | 11.891 | Total heat transfer resistance of the water tank wall |
| $R_{conv,air}$ $(m^2\,K/W)$ | 0.1811 | Heat transfer resistance of air |
| $A_{digester}$ $(m^2)$ | 4.625 | Surface area of the digester |
| $A_{tank}$ $(m^2)$ | 5.6686 | Surface area of the water tank |
| $\dot{Q}_{digester}$ $(W/℃)$ | 0.37 | Rate of heat loss from the digester |
| $\dot{Q}_{tank}$ $(W)$ | 0.453 | Rate of heat loss from the water tank |

## B-1. 6: Feasibility Costing

### B-1.6.1: Component Costs

| | Solar-Aided Digester | | | | Digester Without Heating | | |
|---|---|---|---|---|---|---|---|
| **Entry** | **Price (UgShs)** | **Quantity** | **Cost (UgShs)-2014** | **Updated Cost (UgShs)-2016** | **Quantity** | **Cost (UgShs)-2014** | **Updated Cost (UgShs)-2016** |
| Cement (50kg sack) | 28, 496 | 30 | 854, 880 | 949, 699.87 | 15 | 427, 440 | 474, 849.94 |
| Stainless steel ($m^2$) | 123, 282 | 12 | 1, 479, 384 | 1, 643, 471.36 | 6 | 739, 692 | 821, 735.68 |
| Bricks ($m^2$) | 247 | 500 | 123, 500 | 137, 198.13 | 360 | 88, 920 | 98, 782.65 |
| Pipe (per 6 m) | 22, 688 | 60 | 1, 361, 280 | 1, 512, 267.73 | 10 | 226, 880 | 252, 044.62 |
| Expanded Polystyrene ($m^2$) | 10, 500 | 75 | 787, 500 | 874, 846.35 | 30 | 315, 000 | 349, 938.54 |
| Construction (per $m^2$) | 10, 000 | 60 | 600, 000 | 666, 549.6 | 42 | 420, 000 | 466, 584.72 |
| Sand (Truck) | 100, 000 | 1 | 100, 000 | 111, 091.6 | 1 | 100, 000 | 111, 091.6 |
| 0.5 HP Water Pump | 210, 000 | 1 | 210, 000 | 233, 292.36 | 0 | 0 | 0 |
| 2 HP Concrete Pump | 600, 000 | 1 | 600, 000 | 66, 6549.6 | 1 | 600, 000 | 666, 549.6 |
| Gas Compressor | 105, 000 | 1 | 105, 000 | 116, 646.18 | 1 | 105, 000 | 116, 646.18 |
| Gas Pressure Gauge | 175, 000 | 1 | 175, 000 | 194, 410.3 | 1 | 175, 000 | 194, 410.3 |
| 3-Way valve | 472, 500 | 2 | 945, 000 | 1, 049, 815.62 | 0 | 0 | 0 |
| Glazed Flat Plate Water Heater | 1, 500, 000 | 5 | 7, 500, 000 | 8, 331, 870 | 0 | 0 | 0 |
| **TOTAL** | | | 14,841, 544 | **16, 487, 708.69** | | 3, 197, 932 | **3, 552, 633.826** |
| | | | | | | | |
| O& M Cost | | 0.3% of Investment Cost | | 49, 463.13 | | | 10, 657.9 |
| Equity | | 50% of Investment | | 8, 243, 854.35 | | | 1, 776, 316.91 |
| Insurance | | 0.2% of Investment Cost | | 32, 975.42 | | | 7, 105.27 |
| Annuity | | 10 years' period | | 2, 255, 054.02 | | | 485, 900.21 |

### B-1.6.1: Cost Treatment and Evaluation

| Entry (unit) | Value |
|---|---|
| Plant lifetime (years) | 30 |
| Interest rate (%) | 24.23 |
| Inflation rate (%) | 5.4 |
| Price of firewood (UgShs/kg) | 152 |

## B-1. 7: Environmental Impact Results

| Entry | Value | Description |
|---|---|---|
| $EF_{GHG;wood}$ $(kg_{CO_{2eq.}} \cdot ton_{wood}{}^{-1})$ | 1, 661.924 | Sum of all emission factor for the GHG from the firewood use |
| $EF_{GHG;biogas}$ $(kg_{CO_{2eq.}} \cdot ton_{biogas}{}^{-1})$ | 0.02538 | Sum of all emission factor for the GHG from the biogas use |
| $FS_{wood}$ (kg/year) | 1, 311.57 | Mass of 75% firewood substituted by biogas |
| $EF_{cow}$ $(kg_{CO_{2eq.}} head^{-1} year^{-1})$ | 775 | Emission factor of cattle |
| $N_T$ (cattle) | 7 | Number of cattle per household |
| Mass of biogas (kg/year) | 438 | Mass of biogas used by household |
| $ERES$ $(kg_{CO_{2eq.}} year^{-1})$ | 2, 179.7 | Total emissions for 75 % firewood substituted by biogas |
| $ERMM$ $(kg_{CO_{2eq.}} year^{-1})$ | 2, 224.25 | Total emissions for cattle manure left in open (for 41% used in digester daily) |
| $EBC$ $(kg_{CO_{2eq.}} year^{-1})$ | 0.011 | Total emissions from use of biogas |
| $NET$ $(kg_{CO_{2eq.}} year^{-1})$ | 4, 403.94 | Total emission reduction by using biogas |

## B-1.8: Model Validation Data

## B-1.8.1: Methane production rate for Experimental and Simulation analysis

| | At 34.8 ℃ | | At 35.4 ℃ | |
|---|---|---|---|---|
| **HRT** | **Experiment Rate 1** | **Simulation Rate 1** | **Experiment Rate 2** | **Simulation Rate 2** |
| 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1100 | 871.5 |
| 2 | 810 | 799.1 | 1450 | 1085 |
| 3 | 760 | 1041 | 1380 | 1109 |
| 4 | 970 | 1079 | 1400 | 1072 |
| 5 | 1300 | 1050 | 1240 | 1016 |
| 6 | 990 | 998.5 | 940 | 955.6 |
| 7 | 410 | 941.8 | 1070 | 897.4 |
| 8 | 620 | 886.1 | 970 | 843.3 |
| 9 | 550 | 833.8 | 840 | 793.8 |
| 10 | 350 | 785.7 | 670 | 748.9 |
| 11 | 510 | 741.8 | 640 | 708.1 |
| 12 | 270 | 701.9 | 740 | 671.2 |
| 13 | 360 | 665.7 | 710 | 637.6 |
| 14 | 350 | 632.6 | 640 | 607 |
| 15 | 320 | 602.5 | 660 | 579 |
| 16 | 340 | 575 | 580 | 553.4 |
| 17 | 440 | 549.7 | 570 | 529.9 |
| 18 | 340 | 526.5 | 570 | 508.3 |
| 19 | 300 | 505.1 | 530 | 488.3 |
| 20 | 290 | 485.4 | 530 | 469.7 |
| 21 | 320 | 467 | 500 | 452.5 |
| 22 | 320 | 450 | 450 | 436.5 |
| 23 | 280 | 434.1 | 430 | 421.6 |
| 24 | 280 | 419.3 | 510 | 407.6 |
| 25 | 360 | 405.5 | 420 | 394.5 |
| 26 | 200 | 392.5 | 400 | 382.2 |
| 27 | 270 | 380.3 | 350 | 370.7 |
| 28 | 280 | 368.9 | 330 | 359.8 |
| 29 | 200 | 358.1 | 310 | 349.5 |
| 30 | 170 | 347.9 | 300 | 339.8 |
| 31 | 170 | 338.3 | 270 | 330.6 |
| 32 | 260 | 329.1 | 290 | 321.9 |
| 33 | 140 | 320.5 | 240 | 313.7 |
| 34 | 210 | 312.3 | 250 | 305.8 |

| | At 34.8 ℃ | | At 35.4 ℃ | |
|---|---|---|---|---|
| **HRT** | **Experiment Rate 1** | **Simulation Rate 1** | **Experiment Rate 2** | **Simulation Rate 2** |
| 35 | 230 | 304.5 | 240 | 298.3 |
| 36 | 150 | 297.1 | 280 | 291.2 |
| 37 | 150 | 290 | 70 | 284.4 |
| 38 | 130 | 283.3 | 230 | 278 |
| 39 | 280 | 276.8 | 210 | 271.8 |

## B-1.8.2: Cumulative methane yield for Experimental and Simulation analysis

| | At 34.8 ℃ | | | At 35.5 ℃ | | |
|---|---|---|---|---|---|---|
| **HRT** | **Experiment Yield 1** | **Simulation Yield 1** | **Simulation Rate Sum 1** | **Experiment Yield 2** | **Simulation Yield 2** | **Simulation Rate Sum 2** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 1100 | 1090 | 871.5 |
| 2 | 810 | 1088 | 799.1 | 2550 | 2083 | 1956.5 |
| 3 | 1570 | 2078 | 1840.1 | 3930 | 2986 | 3065.5 |
| 4 | 2540 | 2979 | 2919.1 | 5330 | 3808 | 4137.5 |
| 5 | 3840 | 3800 | 3969.1 | 6570 | 4556 | 5153.5 |
| 6 | 4830 | 4546 | 4967.6 | 7510 | 5237 | 6109.1 |
| 7 | 5240 | 5226 | 5909.4 | 8580 | 5857 | 7006.5 |
| 8 | 5860 | 5844 | 6795.5 | 9550 | 6421 | 7849.8 |
| 9 | 6410 | 6407 | 7629.3 | 10390 | 6935 | 8643.6 |
| 10 | 6760 | 6919 | 8415 | 11060 | 7402 | 9392.5 |
| 11 | 7270 | 7385 | 9156.8 | 11700 | 7827 | 10100.6 |
| 12 | 7540 | 7809 | 9858.7 | 12440 | 8214 | 10771.8 |
| 13 | 7900 | 8196 | 10524.4 | 13150 | 8567 | 11409.4 |
| 14 | 8250 | 8547 | 11157 | 13790 | 8887 | 12016.4 |
| 15 | 8570 | 8867 | 11759.5 | 14450 | 9179 | 12595.4 |
| 16 | 8910 | 9158 | 12334.5 | 15030 | 9445 | 13148.8 |
| 17 | 9350 | 9423 | 12884.2 | 15600 | 9686 | 13678.7 |
| 18 | 9690 | 9664 | 13410.7 | 16170 | 9906 | 14187 |
| 19 | 9990 | 9884 | 13915.8 | 16700 | 10107 | 14675.3 |
| 20 | 10280 | 10084 | 14401.2 | 17230 | 10289 | 15145 |
| 21 | 10600 | 10265 | 14868.2 | 17730 | 10455 | 15597.5 |
| 22 | 10920 | 10431 | 15318.2 | 18180 | 10606 | 16034 |
| 23 | 11200 | 10582 | 15752.3 | 18610 | 10743 | 16455.6 |
| 24 | 11480 | 10719 | 16171.6 | 19120 | 10868 | 16863.2 |
| 25 | 11840 | 10843 | 16577.1 | 19540 | 10982 | 17257.7 |
| 26 | 12040 | 10957 | 16969.6 | 19940 | 11085 | 17639.9 |

| | At 34.8 ℃ | | | At 35.5 ℃ | | |
|---|---|---|---|---|---|---|
| **HRT** | **Experiment Yield 1** | **Simulation Yield 1** | **Simulation Rate Sum 1** | **Experiment Yield 2** | **Simulation Yield 2** | **Simulation Rate Sum 2** |
| 27 | 12310 | 11060 | 17349.9 | 20290 | 11180 | 18010.6 |
| 28 | 12590 | 11154 | 17718.8 | 20620 | 11266 | 18370.4 |
| 29 | 12790 | 11240 | 18076.9 | 20930 | 11344 | 18719.9 |
| 30 | 12960 | 11318 | 18424.8 | 21230 | 11415 | 19059.7 |
| 31 | 13130 | 11389 | 18763.1 | 21500 | 11479 | 19390.3 |
| 32 | 13390 | 11453 | 19092.2 | 21790 | 11538 | 19712.2 |
| 33 | 13530 | 11512 | 19412.7 | 22030 | 11592 | 20025.9 |
| 34 | 13740 | 11566 | 19725 | 22280 | 11641 | 20331.7 |
| 35 | 13970 | 11614 | 20029.5 | 22520 | 11685 | 20630 |
| 36 | 14120 | 11659 | 20326.6 | 22800 | 11725 | 20921.2 |
| 37 | 14270 | 11699 | 20616.6 | 22870 | 11762 | 21205.6 |
| 38 | 14400 | 11736 | 20899.9 | 23100 | 11796 | 21483.6 |
| 39 | 14680 | 11769 | 21176.7 | 23310 | 11826 | 21755.4 |

## B-1.9: Simulation Digester Methane production rate and yield at different temperatures

| Hydraulic Retention Time | Methane Production Rate (50 °C) | Cumulative Methane Yield (50 °C) | Methane Production Rate (21 °C) | Cumulative Methane Yield (21°C) |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 1 | 0.4776 | 0.4776 | 0.02463 | 0.02463 |
| 2 | 2.658 | 3.1356 | 0.3487 | 0.37333 |
| 3 | 2.788 | 5.9236 | 0.5256 | 0.89893 |
| 4 | 2.592 | 8.5156 | 0.6228 | 1.52173 |
| 5 | 2.355 | 10.8706 | 0.6743 | 2.19603 |
| 6 | 2.135 | 13.0056 | 0.6988 | 2.89483 |
| 7 | 1.944 | 14.9496 | 0.7068 | 3.60163 |
| 8 | 1.78 | 16.7296 | 0.7047 | 4.30633 |
| 9 | 1.639 | 18.3686 | 0.6963 | 5.00263 |
| 10 | 1.517 | 19.8856 | 0.684 | 5.68663 |
| 11 | 1.411 | 21.2966 | 0.6694 | 6.35603 |
| 12 | 1.319 | 22.6156 | 0.6536 | 7.00963 |
| 13 | 1.237 | 23.8526 | 0.6371 | 7.64673 |
| 14 | 1.165 | 25.0176 | 0.6205 | 8.26723 |
| 15 | 1.1 | 26.1176 | 0.604 | 8.87123 |
| 16 | 1.043 | 27.1606 | 0.5878 | 9.45903 |
| 17 | 0.9905 | 28.1511 | 0.572 | 10.03103 |
| 18 | 0.9433 | 29.0944 | 0.5567 | 10.58773 |
| 19 | 0.9003 | 29.9947 | 0.5419 | 11.12963 |
| 20 | 0.8611 | 30.8558 | 0.5277 | 11.65733 |
| 21 | 0.825 | 31.6808 | 0.5141 | 12.17143 |
| 22 | 0.7919 | 32.4727 | 0.501 | 12.67243 |
| 23 | 0.7613 | 33.234 | 0.4884 | 13.16083 |
| 24 | 0.733 | 33.967 | 0.4763 | 13.63713 |
| 25 | 0.7066 | 34.6736 | 0.4648 | 14.10193 |
| 26 | 0.6821 | 35.3557 | 0.4537 | 14.55563 |
| 27 | 0.6593 | 36.015 | 0.4431 | 14.99873 |

## B-2.1: System data for November 14th to November 18th

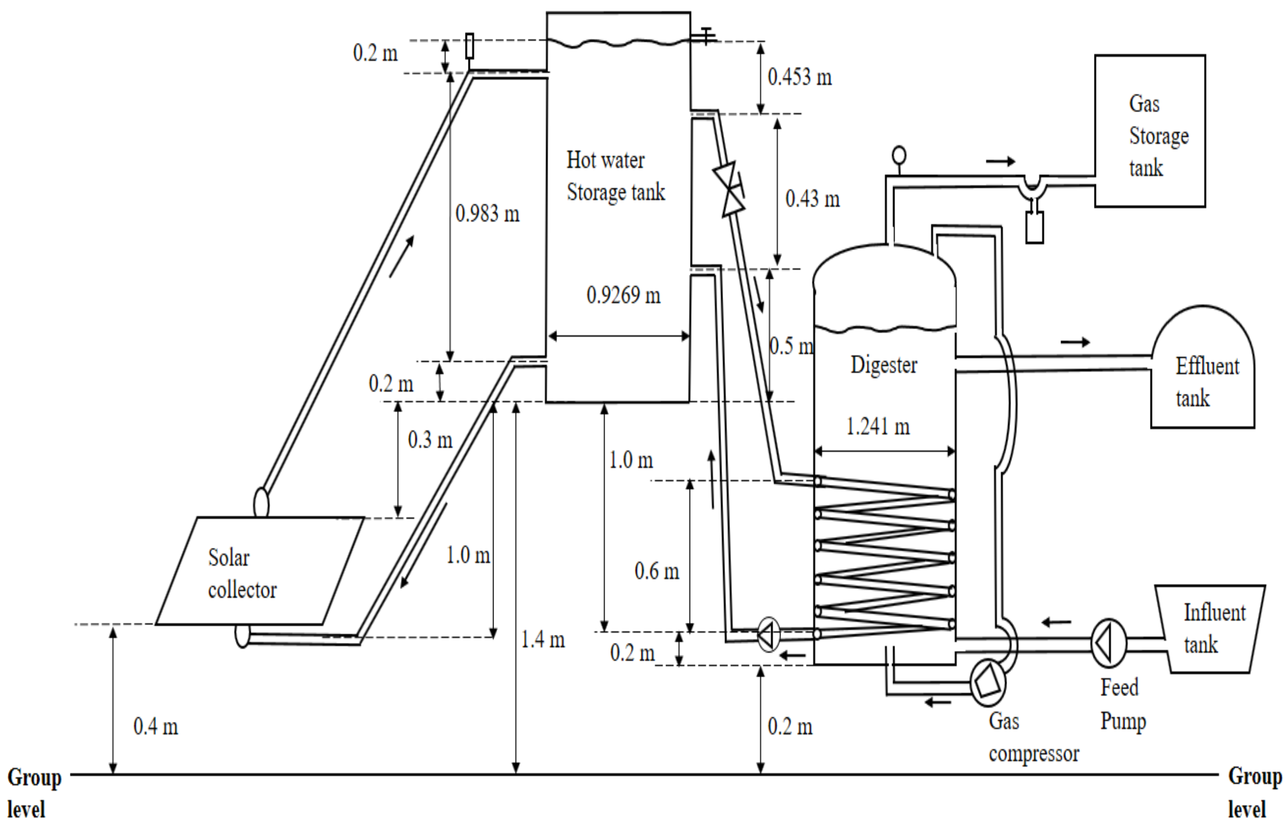
| Annual Time (hours) | T Digester (C) | T tank (C) | T ambient (C ) | T dig. Surface (C ) | T tank. Surface (C ) | Dig. Heat loss (J) | Tank. Heat loss (J) | Irradiance - Incident (W/m2) |
|---|---|---|---|---|---|---|---|---|
| 7609 | 53.83 | 50.2627 | 18.8 | 19.30864 | 19.27918 | 4.60E+04 | 5.40E+04 | 0 |
| 7610 | 53.77 | 50.1867 | 18.6 | 19.11067 | 19.08107 | 4.62E+04 | 5.32E+04 | 0 |
| 7611 | 53.71 | 50.1455 | 18.2 | 18.71561 | 18.68653 | 4.66E+04 | 5.24E+04 | 0 |
| 7612 | 53.66 | 50.112 | 18.1 | 18.61633 | 18.58754 | 4.67E+04 | 5.20E+04 | 0 |
| 7613 | 53.61 | 50.0747 | 17.9 | 18.41851 | 18.39002 | 4.69E+04 | 5.15E+04 | 0 |
| 7614 | 53.55 | 50.0083 | 17.8 | 18.31909 | 18.29053 | 4.69E+04 | 5.22E+04 | 0.98637 |
| 7615 | 53.49 | 49.8108 | 18.2 | 18.71241 | 18.68143 | 4.63E+04 | 4.93E+04 | 41.4276 |
| 7616 | 53.42 | 49.3717 | 18.8 | 19.30268 | 19.26561 | 4.54E+04 | 4.83E+04 | 103.569 |
| 7617 | 53.35 | 48.8817 | 19.3 | 19.79441 | 19.75053 | 4.47E+04 | 4.66E+04 | 138.092 |
| 7618 | 53.27 | 48.5652 | 19.6 | 20.08889 | 20.04114 | 4.42E+04 | 4.59E+04 | 218.39 |
| 7619 | 53.19 | 48.3947 | 20.3 | 20.77756 | 20.72788 | 4.32E+04 | 4.78E+04 | 224.703 |
| 7620 | 53.11 | 48.3075 | 20.5 | 20.9735 | 20.92351 | 4.28E+04 | 4.49E+04 | 224.453 |
| 7621 | 53.03 | 48.2572 | 20.7 | 21.16943 | 21.1197 | 4.24E+04 | 4.50E+04 | 220.448 |
| 7622 | 52.95 | 48.1512 | 20.7 | 21.16827 | 21.11808 | 4.23E+04 | 4.50E+04 | 180.259 |
| 7623 | 52.87 | 48.0015 | 20.7 | 21.16711 | 21.1158 | 4.22E+04 | 4.53E+04 | 150.915 |
| 7624 | 52.79 | 47.8537 | 20.5 | 20.96885 | 20.9166 | 4.24E+04 | 4.54E+04 | 107.514 |
| 7625 | 52.71 | 47.697 | 20.2 | 20.67205 | 20.61878 | 4.27E+04 | 4.56E+04 | 44.3867 |
| 7626 | 52.62 | 47.5124 | 19.7 | 20.178 | 20.12358 | 4.32E+04 | 4.58E+04 | 3.94548 |
| 7627 | 52.53 | 47.2718 | 19.5 | 19.9796 | 19.92296 | 4.34E+04 | 4.62E+04 | 0 |
| 7628 | 52.44 | 46.9877 | 19.1 | 19.5841 | 19.52473 | 4.38E+04 | 4.91E+04 | 0 |
| 7629 | 52.34 | 46.6998 | 18.6 | 19.0899 | 19.02796 | 4.43E+04 | 4.92E+04 | 0 |
| 7630 | 52.24 | 46.437 | 17.1 | 17.61023 | 17.5468 | 4.61E+04 | 4.65E+04 | 0 |
| 7631 | 52.14 | 46.2041 | 18.5 | 18.98845 | 18.92193 | 4.42E+04 | 4.75E+04 | 0 |
| 7632 | 52.03 | 46.0187 | 17.8 | 18.29702 | 18.22977 | 4.49E+04 | 4.75E+04 | 0 |
| 7633 | 51.92 | 45.8903 | 18.3 | 18.78816 | 18.7202 | 4.41E+04 | 4.78E+04 | 0 |
| 7634 | 51.81 | 45.8262 | 18.5 | 18.98366 | 18.91618 | 4.37E+04 | 4.82E+04 | 0 |
| 7635 | 51.71 | 45.7913 | 18.2 | 18.68657 | 18.62022 | 4.40E+04 | 4.81E+04 | 0 |
| 7636 | 51.61 | 45.763 | 18.4 | 18.88221 | 18.81674 | 4.36E+04 | 4.71E+04 | 0 |
| 7637 | 51.51 | 45.7315 | 18.8 | 19.27495 | 19.21017 | 4.29E+04 | 4.55E+04 | 0 |
| 7638 | 51.41 | 45.6755 | 19.2 | 19.66769 | 19.60322 | 4.23E+04 | 4.37E+04 | 0.98637 |
| 7639 | 51.31 | 45.509 | 19.4 | 19.86333 | 19.79764 | 4.19E+04 | 4.20E+04 | 20.7138 |
| 7640 | 51.2 | 45.1388 | 19.7 | 20.15738 | 20.08743 | 4.13E+04 | 4.00E+04 | 57.2095 |
| 7641 | 51.09 | 44.7259 | 19.2 | 19.66304 | 19.58876 | 4.19E+04 | 3.82E+04 | 81.8687 |
| 7642 | 50.97 | 44.3494 | 20.7 | 21.13952 | 21.06018 | 3.97E+04 | 3.70E+04 | 99.6234 |
| 7643 | 50.85 | 44.0277 | 20.9 | 21.33487 | 21.25223 | 3.93E+04 | 3.61E+04 | 120.337 |
| 7644 | 50.72 | 43.7589 | 21.4 | 21.82573 | 21.74053 | 3.85E+04 | 3.58E+04 | 129.215 |
| 7645 | 50.59 | 43.5328 | 21.5 | 21.92239 | 21.83556 | 3.82E+04 | 3.60E+04 | 133.16 |

| Annual Time (hours) | T Digester (C) | T tank (C) | T ambient (C ) | T dig. Surface (C ) | T tank. Surface (C ) | Dig. Heat loss (J) | Tank. Heat loss (J) | Irradiance - Incident (W/m2) |
|---|---|---|---|---|---|---|---|---|
| 7646 | 50.46 | 43.3395 | 20.2 | 20.63938 | 20.55241 | 3.97E+04 | 3.65E+04 | 119.351 |
| 7647 | 50.33 | 43.1676 | 21.8 | 22.21426 | 22.12543 | 3.75E+04 | 3.74E+04 | 93.7052 |
| 7648 | 50.2 | 43.0118 | 21.7 | 22.11382 | 22.02458 | 3.74E+04 | 3.83E+04 | 62.1413 |
| 7649 | 50.07 | 42.8509 | 21.6 | 22.01338 | 21.92365 | 3.74E+04 | 3.90E+04 | 30.5775 |
| 7650 | 49.94 | 42.6632 | 21.3 | 21.71585 | 21.62536 | 3.76E+04 | 3.99E+04 | 3.94548 |
| 7651 | 49.81 | 42.4197 | 21.1 | 21.51687 | 21.4247 | 3.77E+04 | 4.07E+04 | 0 |
| 7652 | 49.67 | 42.1337 | 20.8 | 21.21919 | 21.12491 | 3.79E+04 | 4.12E+04 | 0 |
| 7653 | 49.53 | 41.8459 | 20.5 | 20.92152 | 20.8251 | 3.81E+04 | 4.19E+04 | 0 |
| 7654 | 49.39 | 41.5846 | 20 | 20.42674 | 20.32873 | 3.86E+04 | 4.23E+04 | 0 |
| 7655 | 49.24 | 41.3538 | 18 | 18.4536 | 18.35568 | 4.10E+04 | 4.26E+04 | 0 |
| 7656 | 49.09 | 41.1709 | 17.7 | 18.15578 | 18.05746 | 4.12E+04 | 4.26E+04 | 0 |
| 7657 | 48.95 | 41.0449 | 19 | 19.43487 | 19.33574 | 3.93E+04 | 4.27E+04 | 0 |
| 7658 | 48.81 | 40.9828 | 18.2 | 18.64446 | 18.54698 | 4.02E+04 | 4.30E+04 | 0 |
| 7659 | 48.67 | 40.9496 | 18 | 18.44533 | 18.34952 | 4.03E+04 | 4.26E+04 | 0 |
| 7660 | 48.53 | 40.923 | 17.7 | 18.14765 | 18.05369 | 4.05E+04 | 3.91E+04 | 0 |
| 7661 | 48.39 | 40.8932 | 17.4 | 17.84997 | 17.7578 | 4.07E+04 | 3.47E+04 | 0 |
| 7662 | 48.26 | 40.8391 | 17.4 | 17.84809 | 17.75698 | 4.05E+04 | 3.07E+04 | 0.98637 |
| 7663 | 48.13 | 40.6753 | 18 | 18.43749 | 18.34534 | 3.96E+04 | 2.52E+04 | 61.155 |
| 7664 | 47.99 | 40.4719 | 18.9 | 19.32239 | 19.22854 | 3.82E+04 | 2.19E+04 | 165.472 |
| 7665 | 47.88 | 41.5054 | 19.9 | 20.30627 | 20.22905 | 3.67E+04 | 2.43E+04 | 258.631 |
| 7666 | 47.79 | 42.3496 | 20.7 | 21.09335 | 21.02972 | 3.56E+04 | 2.77E+04 | 310.492 |
| 7667 | 47.73 | 43.6039 | 21.5 | 21.88086 | 21.83664 | 3.44E+04 | 3.07E+04 | 381.392 |
| 7668 | 47.69 | 45.0169 | 22.1 | 22.47157 | 22.44902 | 3.36E+04 | 3.36E+04 | 396.912 |
| 7669 | 47.67 | 46.2546 | 22.4 | 22.76692 | 22.76331 | 3.32E+04 | 3.61E+04 | 366.437 |
| 7670 | 47.67 | 47.1831 | 22.6 | 22.96402 | 22.9744 | 3.29E+04 | 3.96E+04 | 322.47 |
| 7671 | 47.67 | 47.5844 | 22.5 | 22.86547 | 22.88204 | 3.30E+04 | 4.23E+04 | 244.481 |
| 7672 | 47.67 | 47.496 | 22.2 | 22.56982 | 22.58526 | 3.34E+04 | 4.35E+04 | 157.819 |
| 7673 | 47.67 | 47.3593 | 21.7 | 22.07708 | 22.09079 | 3.41E+04 | 4.46E+04 | 76.9369 |
| 7674 | 47.67 | 47.1879 | 21 | 21.38725 | 21.39884 | 3.50E+04 | 4.59E+04 | 3.94548 |
| 7675 | 47.66 | 46.9596 | 20.3 | 20.69727 | 20.70603 | 3.59E+04 | 4.68E+04 | 0 |
| 7676 | 47.65 | 46.6869 | 19.7 | 20.10583 | 20.11101 | 3.67E+04 | 4.79E+04 | 0 |
| 7677 | 47.64 | 46.4089 | 19 | 19.41585 | 19.41744 | 3.76E+04 | 4.88E+04 | 0 |
| 7678 | 47.62 | 46.1544 | 18.3 | 18.72573 | 18.72422 | 3.85E+04 | 5.00E+04 | 0 |
| 7679 | 47.6 | 45.9286 | 17.7 | 18.13415 | 18.12992 | 3.92E+04 | 5.15E+04 | 0 |
| 7680 | 47.58 | 45.7486 | 17 | 17.44402 | 17.43784 | 4.01E+04 | 5.22E+04 | 0 |
| 7681 | 47.56 | 45.6238 | 16.5 | 16.95099 | 16.94356 | 4.08E+04 | 5.30E+04 | 0 |
| 7682 | 47.54 | 45.5614 | 16.1 | 16.55651 | 16.5487 | 4.13E+04 | 5.36E+04 | 0 |
| 7683 | 47.53 | 45.5274 | 15.9 | 16.35927 | 16.35123 | 4.15E+04 | 5.37E+04 | 0 |
| 7684 | 47.5 | 45.4998 | 15.7 | 16.16174 | 16.15385 | 4.17E+04 | 5.08E+04 | 0 |

| Annual Time (hours) | T Digester (C) | T tank (C) | T ambient (C ) | T dig. Surface (C ) | T tank. Surface (C ) | Dig. Heat loss (J) | Tank. Heat loss (J) | Irradiance - Incident (W/m2) |
|---|---|---|---|---|---|---|---|---|
| 7685 | 47.47 | 45.469 | 15.5 | 15.9642 | 15.95643 | 4.20E+04 | 4.67E+04 | 0 |
| 7686 | 47.44 | 45.4145 | 15.7 | 16.16086 | 16.15255 | 4.17E+04 | 4.23E+04 | 4.93185 |
| 7687 | 47.41 | 45.2528 | 17.7 | 18.13139 | 18.11963 | 3.90E+04 | 3.81E+04 | 134.916 |
| 7688 | 47.38 | 44.8934 | 20.3 | 20.6932 | 20.67456 | 3.55E+04 | 3.41E+04 | 365.532 |
| 7689 | 47.35 | 46.8404 | 22.6 | 22.95937 | 22.96918 | 3.25E+04 | 3.49E+04 | 572.642 |
| 7690 | 47.41 | 51.464 | 25.6 | 25.91668 | 25.99391 | 2.86E+04 | 4.10E+04 | 921.176 |
| 7691 | 47.58 | 56.0701 | 27.3 | 27.59447 | 27.73817 | 2.66E+04 | 4.78E+04 | 850.026 |
| 7692 | 47.79 | 57.8303 | 26.9 | 27.20332 | 27.37107 | 2.74E+04 | 5.07E+04 | 442.505 |
| 7693 | 48 | 57.9567 | 25.7 | 26.0238 | 26.19127 | 2.93E+04 | 5.21E+04 | 249.674 |
| 7694 | 48.22 | 58.4922 | 25.2 | 25.53425 | 25.70704 | 3.02E+04 | 5.52E+04 | 359.137 |
| 7695 | 48.45 | 59.202 | 24.9 | 25.24195 | 25.42242 | 3.09E+04 | 5.97E+04 | 381.047 |
| 7696 | 48.67 | 58.9909 | 24.7 | 25.04804 | 25.22225 | 3.15E+04 | 6.08E+04 | 370.692 |
| 7697 | 48.88 | 58.8646 | 23.6 | 23.96707 | 24.13708 | 3.32E+04 | 6.21E+04 | 93.7052 |
| 7698 | 49.08 | 58.6328 | 22.4 | 22.78739 | 22.95183 | 3.50E+04 | 6.31E+04 | 11.8364 |
| 7699 | 49.27 | 58.3053 | 21.6 | 22.00177 | 22.15902 | 3.63E+04 | 6.41E+04 | 0 |
| 7700 | 49.44 | 57.9055 | 20.8 | 21.21585 | 21.36512 | 3.76E+04 | 6.49E+04 | 0 |
| 7701 | 49.6 | 57.4941 | 19.9 | 20.33124 | 20.47256 | 3.90E+04 | 6.57E+04 | 0 |
| 7702 | 49.74 | 57.1157 | 19.1 | 19.54489 | 19.67898 | 4.02E+04 | 9.80E+04 | 0 |
| 7703 | 49.87 | 56.779 | 18.2 | 18.65985 | 18.78756 | 4.16E+04 | 9.74E+04 | 0 |
| 7704 | 49.99 | 56.5104 | 17.4 | 17.87321 | 17.99565 | 4.28E+04 | 9.70E+04 | 0 |
| 7705 | 50.1 | 56.3243 | 16.4 | 16.88932 | 17.00805 | 4.42E+04 | 9.67E+04 | 0 |
| 7706 | 50.21 | 56.2314 | 15.3 | 15.80689 | 15.92339 | 4.58E+04 | 9.65E+04 | 0 |
| 7707 | 50.32 | 56.1811 | 14.7 | 15.2172 | 15.33176 | 4.68E+04 | 9.64E+04 | 0 |
| 7708 | 50.42 | 56.1403 | 14.1 | 14.62737 | 14.74027 | 4.77E+04 | 9.64E+04 | 0 |
| 7709 | 50.52 | 56.0948 | 13.7 | 14.23463 | 14.34567 | 4.83E+04 | 9.63E+04 | 0 |
| 7710 | 50.62 | 56.0136 | 13.6 | 14.13753 | 14.24596 | 4.86E+04 | 9.61E+04 | 0.98637 |
| 7711 | 50.71 | 55.7721 | 15.3 | 15.81415 | 15.91639 | 4.65E+04 | 9.57E+04 | 102.977 |
| 7712 | 50.78 | 55.235 | 17.7 | 18.18032 | 18.27166 | 4.34E+04 | 9.48E+04 | 318.242 |
| 7713 | 50.85 | 56.2791 | 20.2 | 20.64504 | 20.74948 | 4.02E+04 | 9.66E+04 | 533.017 |
| 7714 | 51.01 | 58.9171 | 22.5 | 22.91397 | 23.05463 | 3.74E+04 | 1.01E+05 | 710.454 |
| 7715 | 51.19 | 60 | 24.5 | 24.88754 | 25.04067 | 3.50E+04 | 1.03E+05 | 828.208 |
| 7716 | 51.37 | 60 | 26 | 26.36837 | 26.51782 | 3.33E+04 | 1.03E+05 | 877.043 |
| 7717 | 51.54 | 60 | 27.1 | 27.45487 | 27.60107 | 3.21E+04 | 1.03E+05 | 857.993 |
| 7718 | 51.71 | 60 | 27.7 | 28.04863 | 28.19193 | 3.15E+04 | 1.03E+05 | 763.547 |
| 7719 | 51.87 | 60 | 27.8 | 28.1495 | 28.29041 | 3.16E+04 | 1.03E+05 | 609.58 |
| 7720 | 52.03 | 59.8414 | 27.1 | 27.46198 | 27.59865 | 3.27E+04 | 1.03E+05 | 408.449 |
| 7721 | 52.18 | 59.6235 | 25.8 | 26.18304 | 26.31513 | 3.46E+04 | 1.02E+05 | 203.839 |
| 7722 | 52.32 | 59.355 | 23.9 | 24.31266 | 24.43998 | 3.73E+04 | 1.02E+05 | 13.8092 |
| 7723 | 52.44 | 58.9994 | 23 | 23.42747 | 23.54827 | 3.86E+04 | 1.01E+05 | 0 |

| Annual Time (hours) | T Digester (C) | T tank (C) | T ambient (C ) | T dig. Surface (C ) | T tank. Surface (C ) | Dig. Heat loss (J) | Tank. Heat loss (J) | Irradiance - Incident (W/m2) |
|---|---|---|---|---|---|---|---|---|
| 7724 | 52.55 | 58.5764 | 22.1 | 22.54213 | 22.65554 | 4.00E+04 | 1.01E+05 | 0 |
| 7725 | 52.65 | 58.1464 | 21.3 | 21.7552 | 21.86117 | 4.12E+04 | 9.98E+04 | 0 |
| 7726 | 52.74 | 57.7536 | 20.4 | 20.86958 | 20.9689 | 4.25E+04 | 9.91E+04 | 0 |
| 7727 | 52.82 | 57.4054 | 19.5 | 19.98381 | 20.0773 | 4.37E+04 | 9.85E+04 | 0 |
| 7728 | 52.89 | 57.1283 | 18.6 | 19.09789 | 19.18679 | 4.50E+04 | 9.80E+04 | 0 |

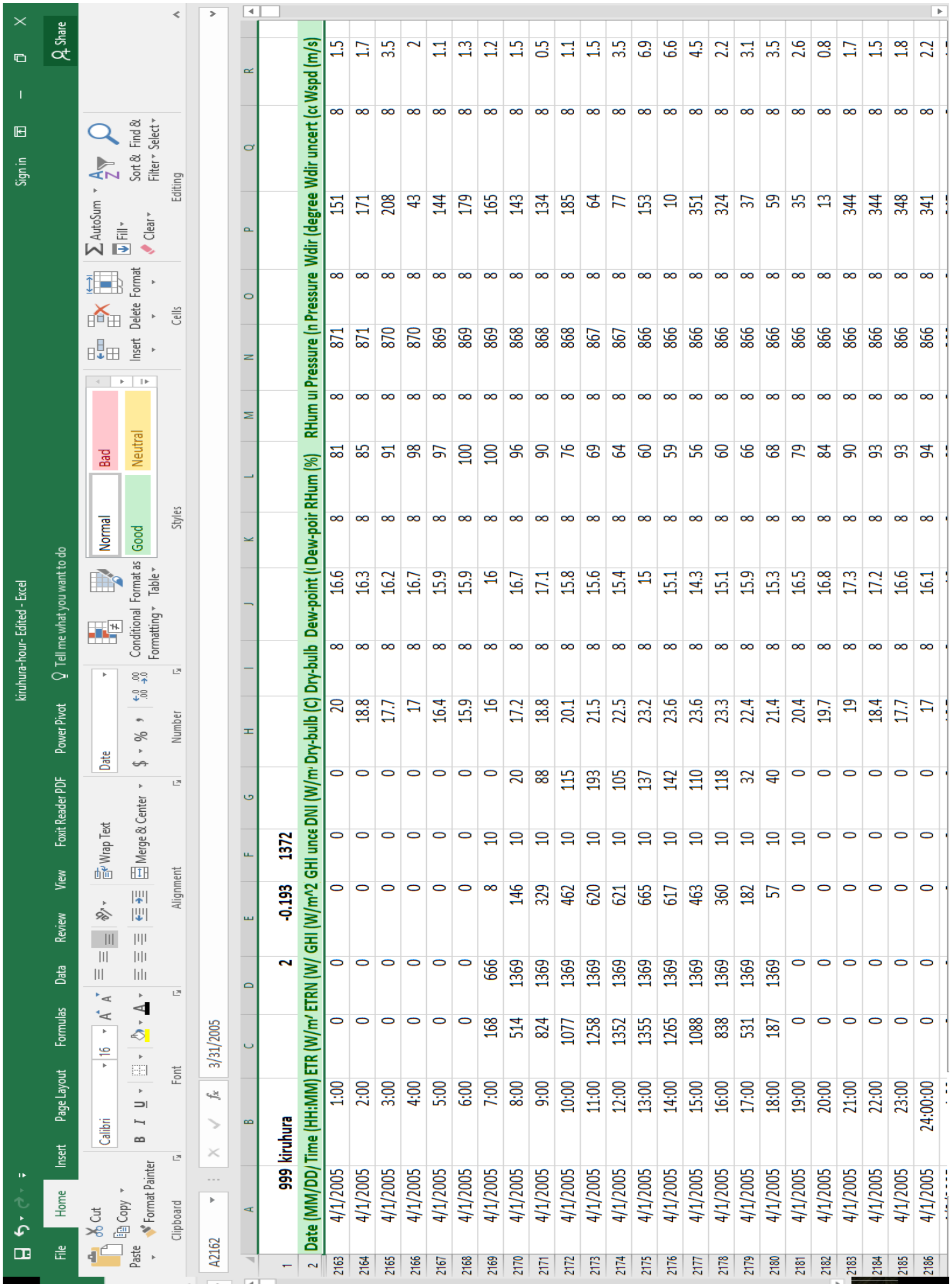
## B-3.1: Schematic Diagram of the System



# Appendix C

## C-1.1 Meteonorm Data for selected days of a year for Kiruhura

| 999 | kiruhura | | 2 | -0.193 | 1372 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date (MM/DD/ | Time (HH:MM) | ETR (W/m^ | ETRN (W/ | GHI (W/m^2 | GHI unce | DNI (W/m | Dry-bulb (C) | Dry-bulb | Dew-point ( | Dew-poir | RHum (%) | RHum u | Pressure (n | Pressure | Wdir (degree | Wdir uncert (ci | Wspd (m/s) |
| 1/1/2005 | 1:00 | 0 | 0 | 0 | 0 | 0 | 18.4 | 8 | 14.1 | 8 | 76 | 8 | 874 | 8 | 173 | 8 | 1.2 |
| 1/1/2005 | 2:00 | 0 | 0 | 0 | 0 | 0 | 17.8 | 8 | 13.5 | 8 | 76 | 8 | 874 | 8 | 207 | 8 | 0.9 |
| 1/1/2005 | 3:00 | 0 | 0 | 0 | 0 | 0 | 17.5 | 8 | 14.2 | 8 | 81 | 8 | 874 | 8 | 249 | 8 | 1 |
| 1/1/2005 | 4:00 | 0 | 0 | 0 | 0 | 0 | 17.2 | 8 | 14 | 8 | 81 | 8 | 874 | 8 | 265 | 8 | 1.2 |
| 1/1/2005 | 5:00 | 0 | 0 | 0 | 0 | 0 | 17 | 8 | 15.4 | 8 | 90 | 8 | 874 | 8 | 263 | 8 | 0.9 |
| 1/1/2005 | 6:00 | 0 | 0 | 0 | 10 | 0 | 17.1 | 8 | 15.8 | 8 | 92 | 8 | 874 | 8 | 252 | 8 | 1.1 |
| 1/1/2005 | 7:00 | 173 | 1412 | 85 | 10 | 382 | 18.2 | 8 | 16.8 | 8 | 91 | 8 | 874 | 8 | 231 | 8 | 0.8 |
| 1/1/2005 | 8:00 | 500 | 1412 | 301 | 10 | 624 | 20.5 | 8 | 16.3 | 8 | 77 | 8 | 874 | 8 | 237 | 8 | 1.4 |
| 1/1/2005 | 9:00 | 794 | 1412 | 521 | 10 | 667 | 23.1 | 8 | 15.8 | 8 | 63 | 8 | 874 | 8 | 169 | 8 | 1.3 |
| 1/1/2005 | 10:00 | 1033 | 1412 | 708 | 10 | 679 | 25.6 | 8 | 15.4 | 8 | 53 | 8 | 874 | 8 | 253 | 8 | 3.5 |
| 1/1/2005 | 11:00 | 1202 | 1412 | 851 | 10 | 703 | 28 | 8 | 15.3 | 8 | 46 | 8 | 874 | 8 | 95 | 8 | 3.2 |
| 1/1/2005 | 12:00 | 1290 | 1412 | 913 | 10 | 669 | 29.9 | 8 | 14.4 | 8 | 39 | 8 | 874 | 8 | 181 | 8 | 3.5 |
| 1/1/2005 | 13:00 | 1289 | 1412 | 907 | 10 | 722 | 31.3 | 8 | 14.5 | 8 | 36 | 8 | 874 | 8 | 145 | 8 | 4.1 |
| 1/1/2005 | 14:00 | 1201 | 1412 | 835 | 10 | 689 | 32.2 | 8 | 15.1 | 8 | 36 | 8 | 873 | 8 | 58 | 8 | 4.6 |
| 1/1/2005 | 15:00 | 1031 | 1412 | 699 | 10 | 656 | 32.6 | 8 | 15.1 | 8 | 35 | 8 | 873 | 8 | 100 | 8 | 4.1 |
| 1/1/2005 | 16:00 | 791 | 1412 | 510 | 10 | 630 | 32.4 | 8 | 15.4 | 8 | 36 | 8 | 873 | 8 | 176 | 8 | 5.1 |
| 1/1/2005 | 17:00 | 498 | 1412 | 292 | 10 | 583 | 31.4 | 8 | 15.1 | 8 | 37 | 8 | 873 | 8 | 81 | 8 | 4.1 |
| 1/1/2005 | 18:00 | 170 | 1412 | 81 | 10 | 356 | 29.9 | 8 | 15.1 | 8 | 41 | 8 | 872 | 8 | 110 | 8 | 4.4 |
| 1/1/2005 | 19:00 | 0 | 0 | 0 | 10 | 0 | 28.3 | 8 | 17.2 | 8 | 51 | 8 | 872 | 8 | 56 | 8 | 3 |
| 1/1/2005 | 20:00 | 0 | 0 | 0 | 0 | 0 | 27.3 | 8 | 16.7 | 8 | 52 | 8 | 872 | 8 | 146 | 8 | 2.6 |
| 1/1/2005 | 21:00 | 0 | 0 | 0 | 0 | 0 | 26.3 | 8 | 16.6 | 8 | 55 | 8 | 871 | 8 | 159 | 8 | 2.2 |
| 1/1/2005 | 22:00 | 0 | 0 | 0 | 0 | 0 | 25.4 | 8 | 16.1 | 8 | 56 | 8 | 871 | 8 | 120 | 8 | 1.3 |
| 1/1/2005 | 23:00 | 0 | 0 | 0 | 0 | 0 | 24.4 | 8 | 16.2 | 8 | 60 | 8 | 871 | 8 | 220 | 8 | 0.9 |
| 1/1/2005 | 24:00:00 | 0 | 0 | 0 | 0 | 0 | 23.4 | 8 | 16.4 | 8 | 65 | 8 | 871 | 8 | 216 | 8 | 0.8 |



| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 999 | kiruhura | | 2 | -0.193 | 1372 | | | | | | | | | | | | |
| 2 | Date (MM/DD/ | Time (HH:MM) | ETR (W/m' | ETRN (W/ | GHI (W/m^2 | GHI unce | DNI (W/m | Dry-bulb (C) | Dry-bulb | Dew-point (I | Dew-poir | RHum (%) | RHum ui | Pressure (n | Pressure | Wdir (degree | Wdir uncert (c | Wspd (m/s) |
| 2163 | 4/1/2005 | 1:00 | 0 | 0 | 0 | 0 | 0 | 20 | 8 | 16.6 | 8 | 81 | 8 | 871 | 8 | 151 | 8 | 1.5 |
| 2164 | 4/1/2005 | 2:00 | 0 | 0 | 0 | 0 | 0 | 18.8 | 8 | 16.3 | 8 | 85 | 8 | 871 | 8 | 171 | 8 | 1.7 |
| 2165 | 4/1/2005 | 3:00 | 0 | 0 | 0 | 0 | 0 | 17.7 | 8 | 16.2 | 8 | 91 | 8 | 870 | 8 | 208 | 8 | 3.5 |
| 2166 | 4/1/2005 | 4:00 | 0 | 0 | 0 | 0 | 0 | 17 | 8 | 16.7 | 8 | 98 | 8 | 870 | 8 | 43 | 8 | 2 |
| 2167 | 4/1/2005 | 5:00 | 0 | 0 | 0 | 0 | 0 | 16.4 | 8 | 15.9 | 8 | 97 | 8 | 869 | 8 | 144 | 8 | 1.1 |
| 2168 | 4/1/2005 | 6:00 | 0 | 0 | 0 | 0 | 0 | 15.9 | 8 | 15.9 | 8 | 100 | 8 | 869 | 8 | 179 | 8 | 1.3 |
| 2169 | 4/1/2005 | 7:00 | 168 | 666 | 8 | 10 | 0 | 16 | 8 | 16 | 8 | 100 | 8 | 869 | 8 | 165 | 8 | 1.2 |
| 2170 | 4/1/2005 | 8:00 | 514 | 1369 | 146 | 10 | 20 | 17.2 | 8 | 16.7 | 8 | 96 | 8 | 868 | 8 | 143 | 8 | 1.5 |
| 2171 | 4/1/2005 | 9:00 | 824 | 1369 | 329 | 10 | 88 | 18.8 | 8 | 17.1 | 8 | 90 | 8 | 868 | 8 | 134 | 8 | 0.5 |
| 2172 | 4/1/2005 | 10:00 | 1077 | 1369 | 462 | 10 | 115 | 20.1 | 8 | 15.8 | 8 | 76 | 8 | 868 | 8 | 185 | 8 | 1.1 |
| 2173 | 4/1/2005 | 11:00 | 1258 | 1369 | 620 | 10 | 193 | 21.5 | 8 | 15.6 | 8 | 69 | 8 | 867 | 8 | 64 | 8 | 1.5 |
| 2174 | 4/1/2005 | 12:00 | 1352 | 1369 | 621 | 10 | 105 | 22.5 | 8 | 15.4 | 8 | 64 | 8 | 867 | 8 | 77 | 8 | 3.5 |
| 2175 | 4/1/2005 | 13:00 | 1355 | 1369 | 665 | 10 | 137 | 23.2 | 8 | 15 | 8 | 60 | 8 | 866 | 8 | 153 | 8 | 6.9 |
| 2176 | 4/1/2005 | 14:00 | 1265 | 1369 | 617 | 10 | 142 | 23.6 | 8 | 15.1 | 8 | 59 | 8 | 866 | 8 | 10 | 8 | 6.6 |
| 2177 | 4/1/2005 | 15:00 | 1088 | 1369 | 463 | 10 | 110 | 23.6 | 8 | 14.3 | 8 | 56 | 8 | 866 | 8 | 351 | 8 | 4.5 |
| 2178 | 4/1/2005 | 16:00 | 838 | 1369 | 360 | 10 | 118 | 23.3 | 8 | 15.1 | 8 | 60 | 8 | 866 | 8 | 324 | 8 | 2.2 |
| 2179 | 4/1/2005 | 17:00 | 531 | 1369 | 182 | 10 | 32 | 22.4 | 8 | 15.9 | 8 | 66 | 8 | 866 | 8 | 37 | 8 | 3.1 |
| 2180 | 4/1/2005 | 18:00 | 187 | 1369 | 57 | 10 | 40 | 21.4 | 8 | 15.3 | 8 | 68 | 8 | 866 | 8 | 59 | 8 | 3.5 |
| 2181 | 4/1/2005 | 19:00 | 0 | 0 | 0 | 10 | 0 | 20.4 | 8 | 16.5 | 8 | 79 | 8 | 866 | 8 | 35 | 8 | 2.6 |
| 2182 | 4/1/2005 | 20:00 | 0 | 0 | 0 | 0 | 0 | 19.7 | 8 | 16.8 | 8 | 84 | 8 | 866 | 8 | 13 | 8 | 0.8 |
| 2183 | 4/1/2005 | 21:00 | 0 | 0 | 0 | 0 | 0 | 19 | 8 | 17.3 | 8 | 90 | 8 | 866 | 8 | 344 | 8 | 1.7 |
| 2184 | 4/1/2005 | 22:00 | 0 | 0 | 0 | 0 | 0 | 18.4 | 8 | 17.2 | 8 | 93 | 8 | 866 | 8 | 344 | 8 | 1.5 |
| 2185 | 4/1/2005 | 23:00 | 0 | 0 | 0 | 0 | 0 | 17.7 | 8 | 16.6 | 8 | 93 | 8 | 866 | 8 | 348 | 8 | 1.8 |
| 2186 | 4/1/2005 | 24:00:00 | 0 | 0 | 0 | 0 | 0 | 17 | 8 | 16.1 | 8 | 94 | 8 | 866 | 8 | 341 | 8 | 2.2 |

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 999 | kiruhura | | 2 | -0.193 | 1372 | | | | | | | | | | | | |
| 2 | Date (MM/DD/ | Time (HH:MM) | ETR (W/m² | ETRN (W/ | GHI (W/m^2 | GHI unce | DNI (W/m | Dry-bulb (C) | Dry-bulb | Dew-point ( | Dew-poir | RHum (%) | RHum u | Pressure (n | Pressure | Wdir (degree | Wdir uncert (c | Wspd (m/s) |
| 5091 | 8/1/2005 | 1:00 | 0 | 0 | 0 | 0 | 0 | 16.7 | 8 | 13.8 | 8 | 83 | 8 | 873 | 8 | 178 | 8 | 3.1 |
| 5092 | 8/1/2005 | 2:00 | 0 | 0 | 0 | 0 | 0 | 15.5 | 8 | 13.7 | 8 | 89 | 8 | 873 | 8 | 223 | 8 | 2.6 |
| 5093 | 8/1/2005 | 3:00 | 0 | 0 | 0 | 0 | 0 | 14.3 | 8 | 13.9 | 8 | 97 | 8 | 873 | 8 | 203 | 8 | 2.3 |
| 5094 | 8/1/2005 | 4:00 | 0 | 0 | 0 | 0 | 0 | 13.7 | 8 | 13.6 | 8 | 99 | 8 | 873 | 8 | 184 | 8 | 2.3 |
| 5095 | 8/1/2005 | 5:00 | 0 | 0 | 0 | 0 | 0 | 13.1 | 8 | 12.9 | 8 | 99 | 8 | 873 | 8 | 205 | 8 | 0.5 |
| 5096 | 8/1/2005 | 6:00 | 0 | 0 | 0 | 0 | 0 | 12.6 | 8 | 12.6 | 8 | 100 | 8 | 873 | 8 | 257 | 8 | 1.3 |
| 5097 | 8/1/2005 | 7:00 | 145 | 625 | 35 | 10 | 0 | 13.3 | 8 | 13.3 | 8 | 100 | 8 | 873 | 8 | 223 | 8 | 0.6 |
| 5098 | 8/1/2005 | 8:00 | 465 | 1325 | 294 | 10 | 500 | 16 | 8 | 14.2 | 8 | 89 | 8 | 873 | 8 | 151 | 8 | 1.1 |
| 5099 | 8/1/2005 | 9:00 | 751 | 1325 | 526 | 10 | 778 | 18.6 | 8 | 15 | 8 | 80 | 8 | 873 | 8 | 135 | 8 | 0.4 |
| 5100 | 8/1/2005 | 10:00 | 987 | 1325 | 725 | 10 | 813 | 20.9 | 8 | 13.7 | 8 | 63 | 8 | 872 | 8 | 130 | 8 | 1.9 |
| 5101 | 8/1/2005 | 11:00 | 1155 | 1325 | 872 | 10 | 829 | 22.9 | 8 | 12.3 | 8 | 51 | 8 | 872 | 8 | 144 | 8 | 3.9 |
| 5102 | 8/1/2005 | 12:00 | 1244 | 1325 | 950 | 10 | 833 | 24.5 | 8 | 12 | 8 | 46 | 8 | 872 | 8 | 153 | 8 | 5.6 |
| 5103 | 8/1/2005 | 13:00 | 1249 | 1325 | 956 | 10 | 841 | 25.7 | 8 | 11.7 | 8 | 42 | 8 | 872 | 8 | 181 | 8 | 2.6 |
| 5104 | 8/1/2005 | 14:00 | 1168 | 1325 | 896 | 10 | 866 | 26.3 | 8 | 11.2 | 8 | 39 | 8 | 872 | 8 | 179 | 8 | 2.3 |
| 5105 | 8/1/2005 | 15:00 | 1007 | 1325 | 767 | 10 | 886 | 26.5 | 8 | 12.4 | 8 | 42 | 8 | 872 | 8 | 40 | 8 | 3.9 |
| 5106 | 8/1/2005 | 16:00 | 778 | 1325 | 577 | 10 | 874 | 26.1 | 8 | 12.4 | 8 | 43 | 8 | 872 | 8 | 84 | 8 | 4.8 |
| 5107 | 8/1/2005 | 17:00 | 496 | 1325 | 342 | 10 | 779 | 24.9 | 8 | 12.8 | 8 | 47 | 8 | 872 | 8 | 152 | 8 | 4.2 |
| 5108 | 8/1/2005 | 18:00 | 180 | 1325 | 105 | 10 | 496 | 23.2 | 8 | 13 | 8 | 53 | 8 | 872 | 8 | 235 | 8 | 3.9 |
| 5109 | 8/1/2005 | 19:00 | 0 | 31 | 0 | 10 | 0 | 21.4 | 8 | 12.1 | 8 | 55 | 8 | 872 | 8 | 145 | 8 | 1.4 |
| 5110 | 8/1/2005 | 20:00 | 0 | 0 | 0 | 0 | 0 | 20.2 | 8 | 14.3 | 8 | 69 | 8 | 873 | 8 | 277 | 8 | 1 |
| 5111 | 8/1/2005 | 21:00 | 0 | 0 | 0 | 0 | 0 | 19.1 | 8 | 13.1 | 8 | 68 | 8 | 873 | 8 | 164 | 8 | 1.6 |
| 5112 | 8/1/2005 | 22:00 | 0 | 0 | 0 | 0 | 0 | 17.9 | 8 | 12.8 | 8 | 72 | 8 | 873 | 8 | 190 | 8 | 1.6 |
| 5113 | 8/1/2005 | 23:00 | 0 | 0 | 0 | 0 | 0 | 16.8 | 8 | 12.3 | 8 | 75 | 8 | 873 | 8 | 214 | 8 | 2.3 |
| 5114 | 8/1/2005 | 24:00:00 | 0 | 0 | 0 | 0 | 0 | 15.6 | 8 | 11.5 | 8 | 77 | 8 | 873 | 8 | 268 | 8 | 0.6 |

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 999 | kiruhura | | 2 | -0.193 | 1372 | | | | | | | | | | | | |
| 2 | Date (MM/DD/ | Time (HH:MM) | ETR (W/m' | ETRN (W/ | GHI (W/m^2 | GHI unce | DNI (W/m | Dry-bulb (C) | Dry-bulb | Dew-point (( | Dew-poir | RHum (%) | RHum ui | Pressure (n | Pressure | Wdir (degree | Wdir uncert (c | Wspd (m/s) |
| 8019 | 12/1/2005 | 1:00 | 0 | 0 | 0 | 0 | 0 | 14.6 | 8 | 14.3 | 8 | 98 | 8 | 872 | 8 | 167 | 8 | 0.9 |
| 8020 | 12/1/2005 | 2:00 | 0 | 0 | 0 | 0 | 0 | 13.9 | 8 | 13.9 | 8 | 100 | 8 | 872 | 8 | 90 | 8 | 0.7 |
| 8021 | 12/1/2005 | 3:00 | 0 | 0 | 0 | 0 | 0 | 13.6 | 8 | 13.6 | 8 | 100 | 8 | 872 | 8 | 124 | 8 | 0.6 |
| 8022 | 12/1/2005 | 4:00 | 0 | 0 | 0 | 0 | 0 | 13.3 | 8 | 13.3 | 8 | 100 | 8 | 873 | 8 | 359 | 8 | 0.4 |
| 8023 | 12/1/2005 | 5:00 | 0 | 0 | 0 | 0 | 0 | 13.1 | 8 | 13.1 | 8 | 100 | 8 | 873 | 8 | 95 | 8 | 0.7 |
| 8024 | 12/1/2005 | 6:00 | 10 | 169 | 1 | 10 | 0 | 13.2 | 8 | 13.2 | 8 | 100 | 8 | 873 | 8 | 187 | 8 | 0.9 |
| 8025 | 12/1/2005 | 7:00 | 251 | 1404 | 156 | 10 | 657 | 15.1 | 8 | 15.1 | 8 | 100 | 8 | 874 | 8 | 180 | 8 | 0.6 |
| 8026 | 12/1/2005 | 8:00 | 574 | 1404 | 428 | 10 | 904 | 18 | 8 | 16.3 | 8 | 90 | 8 | 874 | 8 | 226 | 8 | 0.4 |
| 8027 | 12/1/2005 | 9:00 | 858 | 1404 | 689 | 10 | 1002 | 21.1 | 8 | 14.5 | 8 | 66 | 8 | 874 | 8 | 288 | 8 | 1.1 |
| 8028 | 12/1/2005 | 10:00 | 1083 | 1404 | 899 | 10 | 1040 | 24 | 8 | 15 | 8 | 57 | 8 | 874 | 8 | 306 | 8 | 1.8 |
| 8029 | 12/1/2005 | 11:00 | 1235 | 1404 | 1039 | 10 | 1057 | 26.6 | 8 | 14.1 | 8 | 46 | 8 | 875 | 8 | 106 | 8 | 3.2 |
| 8030 | 12/1/2005 | 12:00 | 1303 | 1404 | 1099 | 10 | 1063 | 28.6 | 8 | 13.5 | 8 | 39 | 8 | 875 | 8 | 106 | 8 | 3.2 |
| 8031 | 12/1/2005 | 13:00 | 1282 | 1404 | 1077 | 10 | 1059 | 30.1 | 8 | 12.8 | 8 | 35 | 8 | 875 | 8 | 162 | 8 | 2.9 |
| 8032 | 12/1/2005 | 14:00 | 1174 | 1404 | 978 | 10 | 1046 | 31 | 8 | 13.1 | 8 | 34 | 8 | 875 | 8 | 339 | 8 | 1.9 |
| 8033 | 12/1/2005 | 15:00 | 986 | 1404 | 800 | 10 | 1022 | 31.2 | 8 | 13.4 | 8 | 34 | 8 | 875 | 8 | 291 | 8 | 2.1 |
| 8034 | 12/1/2005 | 16:00 | 731 | 1404 | 563 | 10 | 964 | 30.7 | 8 | 13.6 | 8 | 35 | 8 | 875 | 8 | 301 | 8 | 2.1 |
| 8035 | 12/1/2005 | 17:00 | 426 | 1404 | 292 | 10 | 520 | 29.3 | 8 | 13.1 | 8 | 37 | 8 | 875 | 8 | 226 | 8 | 2.5 |
| 8036 | 12/1/2005 | 18:00 | 101 | 540 | 20 | 10 | 0 | 27.2 | 8 | 12.5 | 8 | 40 | 8 | 875 | 8 | 291 | 8 | 3.6 |
| 8037 | 12/1/2005 | 19:00 | 0 | 0 | 0 | 0 | 0 | 25.9 | 8 | 14.6 | 8 | 50 | 8 | 875 | 8 | 286 | 8 | 2.7 |
| 8038 | 12/1/2005 | 20:00 | 0 | 0 | 0 | 0 | 0 | 24.6 | 8 | 14.1 | 8 | 52 | 8 | 874 | 8 | 326 | 8 | 1.2 |
| 8039 | 12/1/2005 | 21:00 | 0 | 0 | 0 | 0 | 0 | 23.2 | 8 | 13.3 | 8 | 53 | 8 | 874 | 8 | 302 | 8 | 0.6 |
| 8040 | 12/1/2005 | 22:00 | 0 | 0 | 0 | 0 | 0 | 21.9 | 8 | 12.9 | 8 | 57 | 8 | 874 | 8 | 337 | 8 | 0.4 |
| 8041 | 12/1/2005 | 23:00 | 0 | 0 | 0 | 0 | 0 | 20.6 | 8 | 13.2 | 8 | 63 | 8 | 874 | 8 | 59 | 8 | 0.9 |
| 8042 | 12/1/2005 | 24:00:00 | 0 | 0 | 0 | 0 | 0 | 19.2 | 8 | 12.5 | 8 | 65 | 8 | 874 | 8 | 12 | 8 | 1.4 |

## C-2.1 Monthly Average Weather Data of Kiruhura

**kiruhura**

Radiation | Temperature | Precipitation | Sunshine duration
Daily global radiation | Daily temperature | Data table

| | Gh kWh/m² | Dh kWh/m² | Bn kWh/m² | Ta °C | Td °C | FF m/s |
|---|---|---|---|---|---|---|
| January | 156 | 68 | 132 | 21.7 | 13.9 | 3 |
| February | 141 | 70 | 101 | 22.6 | 12.9 | 3.2 |
| March | 164 | 72 | 127 | 22.3 | 14.6 | 3 |
| April | 154 | 67 | 119 | 21.4 | 15.9 | 2.4 |
| May | 164 | 63 | 147 | 20.9 | 15.9 | 2.2 |
| June | 154 | 62 | 139 | 20.2 | 14.7 | 2.2 |
| July | 156 | 64 | 135 | 19.9 | 14.2 | 2.3 |
| August | 156 | 72 | 120 | 20.1 | 14.4 | 2.4 |
| September | 160 | 73 | 122 | 20.8 | 14.3 | 2.5 |
| October | 160 | 72 | 126 | 21.4 | 14.8 | 2.6 |
| November | 149 | 75 | 108 | 21 | 15.4 | 2.5 |
| December | 155 | 74 | 119 | 21.5 | 14.6 | 2.8 |
| Year | 1868 | 833 | 1497 | 21.1 | 14.6 | 2.6 |

## C-3.1 Financial Analysis Data

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | | | | |
| 2 | | | | | | | | SOLAR-AIDED DIGESTER SYSTEM | | | | | | | | | | | |
| 3 | **Period** | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 4 | **Costs** | | | | | | | | | | | | | | | | | | |
| 5 | Capital (Equity) | 8243854.35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Annuity | 0 | 2376826.94 | 2505175.59 | 2640455.08 | 2783039.65 | 2933323.79 | 3091723.28 | 3258676.33 | 3434644.86 | 3620115.68 | 3815601.92 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Insurance (Power Station) | 0 | 34756.09 | 36632.92 | 38611.10 | 40696.10 | 42893.69 | 45209.95 | 47651.28 | 50224.45 | 52936.57 | 55795.15 | 58808.09 | 61983.72 | 65330.85 | 68858.71 | 72577.08 | 76496.24 | 80627.04 |
| 8 | O & M | 0 | 52134.14 | 54949.38 | 57916.65 | 61044.15 | 64340.53 | 67814.92 | 71476.93 | 75336.68 | 79404.86 | 83692.72 | 88212.13 | 92975.59 | 97996.27 | 103288.07 | 108865.62 | 114744.37 | 120940.56 |
| 9 | Total Cost | 8243854.35 | 2463717.17 | 2596757.90 | 2736982.83 | 2884779.90 | 3040558.01 | 3204748.14 | 3377804.54 | 3560205.99 | 3752457.11 | 3955089.80 | 147020.22 | 154959.31 | 163327.11 | 172146.78 | 181442.70 | 191240.61 | 201567.60 |
| 10 | Net Worth Cost | 8243854.35 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 2337492.57 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 |
| 11 | **Benefits** | | | | | | | | | | | | | | | | | | |
| 12 | Biogas (m3) | 0 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 |
| 13 | Energy Equivalent (kWh) | 0 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 |
| 14 | Degraded Energy Equivalent | 0 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 |
| 15 | | | | | | | | | | | | | | | | | | | |
| 16 | Total Benefit | 0 | 1985387.89 | 2092598.83 | 2205599.17 | 2324701.52 | 2450235.41 | 2582548.12 | 2722005.72 | 2868994.02 | 3023919.70 | 3187211.37 | 3359320.78 | 3540724.10 | 3731923.20 | 3933447.06 | 4145853.20 | 4369729.27 | 4605694.65 |
| 17 | Net Worth Benefit | 0 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 |
| 18 | Cash flow | -8243854 | -478329.29 | -504159.07 | -531383.66 | -560078.37 | -590322.61 | -622200.03 | -655798.83 | -691211.97 | -728537.41 | -767878.43 | 3212300.56 | 3385764.79 | 3568596.09 | 3761300.28 | 3964410.49 | 4178488.66 | 4404127.05 |
| 19 | **Payback Period** | 10.24 | | | | | | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | | | | | | | | |
| 21 | | | | | | | | DIGESTER WITHOUT HEATING SYSTEM | | | | | | | | | | | |
| 22 | **Period** | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 23 | **Costs** | | | | | | | | | | | | | | | | | | |
| 24 | Capital (Equity) | 1776316.91 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | Annuity | 0 | 512138.827 | 539794.32 | 568943.22 | 599666.15 | 632048.12 | 666178.72 | 702152.37 | 740068.6 | 780032.3 | 822154.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | Insurance (Power Station) | 0 | 7488.95458 | 7893.3581 | 8319.5995 | 8768.8578 | 9242.3762 | 9741.4645 | 10267.504 | 10821.949 | 11406.334 | 12022.276 | 12671.479 | 13355.739 | 14076.949 | 14837.104 | 15638.308 | 16482.776 | 17372.846 |
| 27 | O & M | 0 | 11233.4266 | 11840.032 | 12479.393 | 13153.281 | 13863.558 | 14612.19 | 15401.248 | 16232.916 | 17109.493 | 18033.406 | 19007.209 | 20033.599 | 21115.413 | 22255.645 | 23457.45 | 24724.153 | 26059.257 |
| 28 | Total Cost | 1776316.91 | 530861.208 | 559527.71 | 589742.21 | 621588.29 | 655154.06 | 690532.38 | 727821.12 | 767123.46 | 808548.13 | 852209.73 | 31678.688 | 33389.338 | 35192.362 | 37092.749 | 39095.758 | 41206.929 | 43432.103 |
| 29 | Net Worth Cost | 1776316.91 | 503663.385 | 503663.38 | 503663.38 | 503663.38 | 503663.38 | 503663.38 | 503663.38 | 503663.38 | 503663.38 | 503663.38 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 |
| 30 | **Benefits** | | | | | | | | | | | | | | | | | | |
| 31 | Biogas (m3) | 0 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 |
| 32 | Energy Equivalent (kWh) | 0 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 |
| 33 | Degraded Energy Equivalent | 0 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 |
| 34 | | | | | | | | | | | | | | | | | | | |
| 35 | Total Benefit | 0 | 827046.143 | 871706.63 | 918778.79 | 968392.85 | 1020686.1 | 1075803.1 | 1133896.5 | 1195126.9 | 1259663.7 | 1327685.6 | 1399380.6 | 1474947.2 | 1554594.3 | 1638542.4 | 1727023.7 | 1820283 | 1918578.2 |
| 36 | Net Worth Benefit | 0 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 |
| 37 | Cash flow | -1776317 | 296184.935 | 312178.92 | 329036.58 | 346804.56 | 365532.01 | 385270.73 | 406075.35 | 428003.42 | 451115.61 | 475475.85 | 1367701.9 | 1441557.8 | 1519401.9 | 1601449.6 | 1687927.9 | 1779076 | 1875146.1 |
| 38 | **PayBack Period** | 6.00 | | | | | | | | | | | | | | | | | |
| 39 | | | | | | | | | | | | | | | | | | | |

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| | A | T | U | V | W | X | Y | Z | AA | AB | AC | AD | AE | AF | AG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | |
| 2 | | | | | | SOLAR-AIDED DIGESTER SYSTEM | | | | | | | | | |
| 3 | **Period** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** | **Total** |
| 4 | **Costs** | | | | | | | | | | | | | | |
| 5 | Capital (Equity) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 6 | Annuity | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 7 | Insurance (Power Station) | 84980.90 | 89569.87 | 94406.64 | 99504.60 | 104877.85 | 110541.25 | 116510.48 | 122802.05 | 129433.36 | 136422.76 | 143789.59 | 151554.23 | 159738.15 | |
| 8 | O & M | 127471.35 | 134354.80 | 141609.96 | 149256.90 | 157316.77 | 165811.88 | 174765.72 | 184203.07 | 194150.04 | 204634.14 | 215684.38 | 227331.34 | 239607.23 | |
| 9 | Total Cost | 212452.25 | 223924.67 | 236016.61 | 248761.50 | 262194.62 | 276353.13 | 291276.20 | 307005.12 | 323583.39 | 341056.90 | 359473.97 | 378885.57 | 399345.39 | |
| 10 | Net Worth Cost | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | 82438.55 | **33267551.1** |
| 11 | **Benefits** | | | | | | | | | | | | | | |
| 12 | Biogas (m3) | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | 811.40 | |
| 13 | Energy Equivalent (kWh) | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | **146051.1** |
| 14 | Degraded Energy Equivalent | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | 4868.37 | **146051.1** |
| 15 | | | | | | | | | | | | | **LCOE** | | **227.78** |
| 16 | Total Benefit | 4854402.16 | 5116539.88 | 5392833.03 | 5684046.01 | 5990984.50 | 6314497.66 | 6655480.54 | 7014876.48 | 7393679.82 | 7792938.53 | 8213757.21 | 8657300.09 | 9124794.30 | |
| 17 | Net Worth Benefit | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | 1883669.72 | **56510091.61** |
| 18 | Cash flow | 4641949.91 | 4892615.20 | 5156816.42 | 5435284.51 | 5728789.87 | 6038144.53 | 6364204.33 | 6707871.37 | 7070096.42 | 7451881.63 | 7854283.23 | 8278414.53 | 8725448.91 | |
| 19 | **Payback Period** | | | | | | | | | | | | **COST-BENEFIT** | | **0.589** |
| 20 | | | | | | | | | | | | | | | |
| 21 | | | | | | DIGESTER WITHOUT HEATING SYSTEM | | | | | | | | | |
| 22 | **Period** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** | |
| 23 | **Costs** | | | | | | | | | | | | | | |
| 24 | Capital (Equity) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 25 | Annuity | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 26 | Insurance (Power Station) | 18310.98 | 19299.773 | 20341.96 | 21440.426 | 22598.209 | 23818.513 | 25104.712 | 26460.367 | 27889.226 | 29395.245 | 30982.588 | 32655.648 | 34419.0526 | |
| 27 | O & M | 27466.457 | 28949.645 | 30512.926 | 32160.624 | 33897.298 | 35727.752 | 37657.051 | 39690.531 | 41833.82 | 44092.846 | 46473.86 | 48983.448 | 51628.5547 | |
| 28 | Total Cost | 45777.436 | 48249.418 | 50854.887 | 53601.05 | 56495.507 | 59546.265 | 62761.763 | 66150.898 | 69723.046 | 73488.091 | 77456.448 | 81639.096 | 86047.6073 | |
| 29 | Net Worth Cost | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | 17763.17 | **7168214.16** |
| 30 | **Benefits** | | | | | | | | | | | | PRESENT COST VALUE | | **7168214.16** |
| 31 | Biogas (m3) | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | |
| 32 | Energy Equivalent (kWh) | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | **60840** |
| 33 | Degraded Energy Equivalent | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | 2028 | **60840** |
| 34 | | | | | | | | | | | | | **LCOE** | | **117.82** |
| 35 | Total Benefit | 2022181.5 | 2131379.3 | 2246473.7 | 2367783.3 | 2495643.6 | 2630408.4 | 2772450.4 | 2922162.8 | 3079959.5 | 3246277.4 | 3421576.3 | 3606341.5 | 3801083.9 | |
| 36 | Net Worth Benefit | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | 784673.76 | **23540212.8** |
| 37 | Cash flow | 1976404 | 2083129.8 | 2195618.9 | 2314182.3 | 2439148.1 | 2570862.1 | 2709688.7 | 2856011.9 | 3010236.5 | 3172789.3 | 3344119.9 | 3524702.4 | 3715036.3 | |
| 38 | **PayBack Period** | | | | | | | | | | | **Cost-Benefit Ratio** | | | **0.305** |
| 39 | | | | | | | | | | | | | | | |