Evaluation of Biogas Driven Poly-generation System to Reduce Energy Poverty and Post-harvest Loss

Thesis by

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Abstracts

Electricity has been described as “the missing link” of the sustainable development goals: as other goals are strongly linked to its availability. Currently, most rural communities are at the bottom of the energy ladder and majority of the dwellers are farmers who suffer from heavy post-harvest loss due to facilities deficiency. These remote areas, which often have plenty of biomass, are isolated and sparsely populated where grid connections are mostly economically or topographically unfeasible. The conventional solutions to rural energy usually look into electricity provision without linking the same to the farming activities which is the means of farmers’ livelihood. Thus, having little impact on improving farmers’ standard of living.

To ensure clean energy access, a biogas driven combined cooling, heat and power generation system which harmonizes electricity generation with food drying and cold storage of agricultural products is studied in the context of the current renewable energy policy of the Nigerian government. Jagun village, an agrarian community in Oyo State South western part of Nigeria was used as case study. Primary and secondary data are used to assess the current level of post-harvest waste, biomass resources as well as energy demand. Wastes from a community cattle market and agricultural crops residue are quantified, characterised and assessed for biogas generation. Part of the biogas produced is used for household cooking while the remaining is used to power an internal combustion engine for electricity generation. Heat recovered from the engine is used to drive a cabinet dryer, an absorption chiller and maintain anaerobic digestion process. Besides, the effluent of the digester is assessed for the organic fertiliser. The models of the anaerobic digestion process, purification unit, internal combustion engine, drying unit and absorption chiller were developed in Aspen Plus software and the results are used to evaluate the economic viability of the system. The economic viability of the system was assessed for: electricity generation only; combined power and cooling (CCP), combined power and drying (CCD) and trigeneration system (CCDP.

The results demonstrate that about 4, 666 kg/day of biogas can be generated from the village’s agricultural waste. It is estimated that the biogas can drive a 72kW internal combustion engine which is enough to produce electricity for about 420 rural households. The recovered heat from the process is enough to dry about 1,584.8 kg.day^{-1} of High-Quality Cassava Flour while 555.33 kg.day^{-1} of tomato can be cold stored. Cold storage of tomato can be used to control market glutting which currently accounts for the postharvest loss of up 474 kg/ha within the studied area. Recovery of heat from the system increases the system efficiency from 26.73%

to 68.4-71.4 depending the operational parameters and extent of heat recovery. The results also suggest that, given the current Nigerian rural electricity tariff of USD0.013/kWh and without feed in tariffs, an electricity only generation system is not currently economically viable as the system fails to payback during its life span. At the newly proposed Rural Electrification Agency tariff of 0.089/kWh, the discounted payback period (DPP) is around 17 years for the electricity only system.

At a proposed tariff of USD0.05/kWh for the combined generation systems, electricity contributes about 31.43% to the income generation while contributions from processed crops varies between 34% to 68.75 depending on the prices of the agricultural produce handled. Depending on the type and prices of agricultural products handled, the DPP is 6-8 years, 5.3-6.0 years and 2.5-4.7 yeas respectively for CCP, CCD and CCDP systems. More so, such systems will benefit more from handling of "cash crops" than "staple foods" crops. In addition to being feasible, combined generation systems for rural areas are capable of enhancing rural energy security, food security, climate change abatement as well as reducing deaths related to fuelwood induced smoking during cooking which is prevalent in the Sub-Saharan African region.

Dedication

This humble work is lovingly dedicated to two people without whom none of my success would be possible. Though they are no longer of this world, their memories continue to shape my life.

Dr. Eniola Babarinde *(my secondary school principal)*

&

Mrs. Jemilat Kareem Owonikoko *(my beloved mum)*

You thought me the values of life. “E seun”

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List of Publications

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iii) **Rasaq. O. Lamidi**, L. Jiang, Pankaj B. Pathare, Y. D. Wang, A.P. Roskilly, Recent advances in sustainable drying of agricultural produce: A review, *Applied Energy*, 233–234, 2019, Pages 367–385.

Reviewed Conference Papers

i) **Rasaq O. Lamidi**, Yao Dong Wang, Pankaj B. Pathare, A. P. Roskilly, Evaluation of CHP for Electricity and Drying of Agricultural Products in a Nigerian Rural Community, *Energy Procedia*, Volume 105, May 2017, Pages 47-54.

ii) **Rasaq O. Lamidi**, Yaodong Wang, Pankaj B. Pathare, A. P. Roskilly, Marcelo Calispa Aguilar, Biogas Tri-generation for Postharvest Processing of Agricultural Products in a Rural Community: Techno-economic Perspectives, *Energy Procedia*, Volume 142, December 2017, Pages 63-69.

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Other publications related to this research:

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Nomenclature

General sign

A	Area (m^2)
BP	Break Power (kJ/hr)
Cp	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
H	Latent Heat ($kJkg^{-1}$)
kW	Kilowatt
kWh	Kilowatt hour
M	Mass (kg)
MT	Metric tonnes
MWhe	Megawatt hour electricity
P	Pressure
Q	Heat (kJ/hr)
U	Useful Energy
UA	Overall Heat Transfer Coefficient
W	Weight (kg)
r	Interest rate (%)

Acronyms

ABS	Absorber
AD	Anaerobic Digestion
ADM	Anaerobic Digestion Modelling
ARS	Absorption Refrigeration System
AP	Aspen Plus
RS	Rich Solution
AWS	Ammonia Weak Solution
BESP	Break-Even Selling Point
CCP	Combined Cooling and Power
CCHP	Combine Cooling Heat and Power
CHP	Combine Heat and Power
COD	Chemical Oxygen Demand
CON	Condenser
COP	Coefficient of Performance

DCI	Discounted Cash Inflow
DES	Distributed Energy System
DPP	Discounted Payback Period
EDM	Energy Demand Management
EVAP	Evaporator
FITs	Feed –in- Tariffs
GEN	Generator
HP	Heat pump
HQCF	High Quality Cassava Flour
HRT	Hydraulic Retention Time
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
LCOE	Levelise Cost of Energy
LHV	Low Heat Value
LNG	Liquefied Natural Gas
LPG	Liquid Petroleum Gas
MC	Moisture content
NBC	Nigeria Bureau of Statistics
NEPA	National Electricity Power Authority
NERC	Nigerian Electricity Regulatory Commission
NG	Natural gas
NPV	Net Present Value
OLR	Organic Loading Rate
ORC	Organic Rankine cycle
PH	Post-harvest
PHL	Post-harvest Loss
PI	Profitability Index
PR	Crop Production
RE	Renewable Energy
REA	Rural Electrification Agency
REF	Rural Electrification Fund
RS	Residue

SCF	Sundried Cassava Flour
SDGs	Sustainable Development Goals
SS	Strong Solution
SSA	Sub-Saharan African
SRT	Solid Retention Time
STH	Shell and Tube Heat Exchanger
TCN	Transmission Company of Nigeria
TDM	Thermal Demand Management
TS	Total Solids
USD	United States of America Dollar
VS	Volatile Solids
WS	Weak Solution

Subscripts

a	air
amb	ambient
avl	availability
b	Biogas
bm	Biogas mixing
c	cassava
cu	Current
cs	cold storage
d	digestion
dr	digester
dry	dryer
cm	Cooling medium
E	energy
ele	electrical
exh	exhaust
hex	heat exchanger
hres	respiratory heat
fr	flow rate
fu	future

fw	fuelwood
hres	respiration heat
i	initial
in	input
ins	insulator
inv	investment
k	kerosene
l	loss
LMTD	Logarithm Mean Temperature Difference
m	mean
misc	miscellaneous
n	number of years
out	output
prod	produce
R	reactor
Rad	radiation
res	respiration
s	supplied
sb	substrate
sen	sensible
st	storage
t	total
tm	tomato
v	vaporisation
w	water
wm	warming
y	yam

Greek Signs

ΔH	latent heat, kJ· kg^{-1}
μ	efficiency (%)
$\dot{m}$	mass flowrate (kg/h)
h	enthalpy (J)

ρ	density (kgm^{-3})
g	acceleration due to gravity (Nkg^{-1})
K	thermal conductivity (Wm^{-1}K^{-1}

Chapter 1 : Introduction

1.0 Research background

Energy has been described as the “missing link” of the Sustainable Development Goals (SDGs). This is because other goals: poverty eradication, good health, food security, sustainable communities, economic growth, universal education, clean water and sanitation, climate action e.tc. are strongly linked to the availability of energy. For instance, reducing global poverty which is another objective of SDGs is practically impossible without access to modern energy since economic advancement is directly linked to the increased use of modern energy. More so, the pressure being currently experienced by the earth’s finite resources (land, water, and energy) is expected to be deepened by the projected 30% rise in the global population by 2050 (Gustavsson et al., 2011). To ensure food security for the estimated 8.6 billion people, the food production is expected to increase, at least, by 70%. At the current rate of agricultural productivity India, East Asia and Sub-Saharan African (SSA) region domestic production would only able to meet 59%, 67%, 15% of local food demand respectively (Food and Agriculture Organisation, 2014). Paradoxically, bulk of the projected population growth is from these regions particularly African continent which will account for above 60% of the projected growth. The SSA region also accounts for the highest number of food unsecured households and generally characterised with energy poverty and inefficient agricultural practices which lead to high postharvest losses (PHL). Currently, about one-third (Figure 1-1) of the global food produced for human consumption ends up as waste which results in negative externalities ranging from economic loss, resources wastage and environmental degradation. A recent study revealed that food wastes now ranked third in terms of its contribution to the global CO_2 emission (Food and Agriculture Organisation, 2013). In contrast to what is obtainable in the developed countries, food loss within India, East Asia and Sub-Saharan African (SSA) regions is predominantly within the early stage of food value chain (Stuart, 2009). In these economies, more than 600 MT of food are lost at the postharvest stage and costing about US$ 310 billion annually (Food and Agriculture Organisation, 2014). In SSA countries, about US$4 billion worth of grain is lost between “field and fork” and estimated to be equal to food imported and all the foreign aids received by the region in a decade (Ibid). Arguably, improved energy access in rural communities would not only reduce food loss, increase food security, improve rural economy, enhance standard of living but also improve environmental sustainability since food loss will be prevented. Thus, most of the extra food demand can be met through reduction of PHL waste (Kummu et al., 2012).

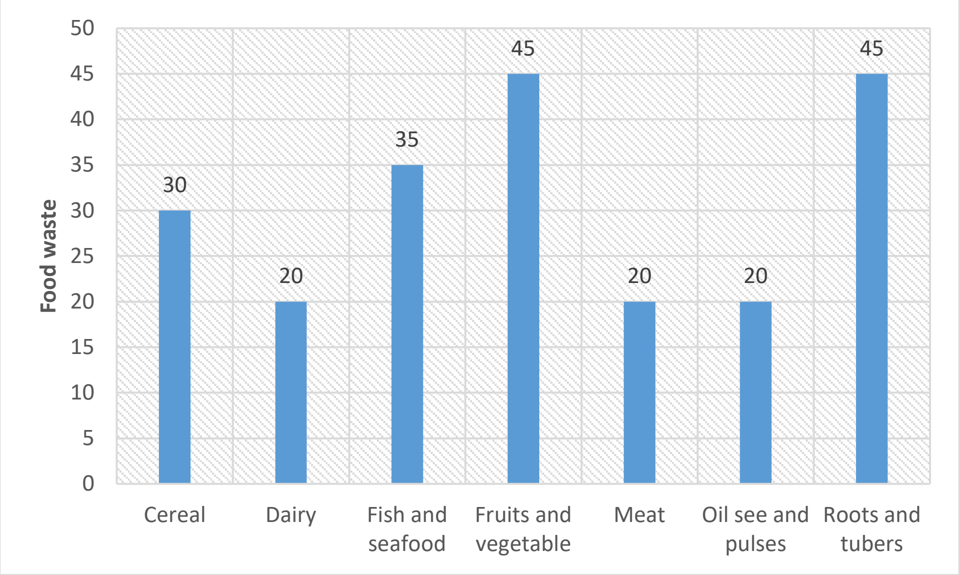


Figure 1-1: Food waste across different food types (Food and Agriculture Organisation, 2012)

In addition, the negative externalities associated with fossil fuels coupled with its price volatility and the challenges of centralised grid systems makes renewable energy a preferred alternative when seeking to increase energy accessibility of the rural communities, particularly remote and bad topographical areas. In this case, distributed energy system (DES) will be a better choice (Ghaem Sigarchian et al., 2015). This is because distributed energy is localised i.e. produced and utilised onsite or close to its source of generation. Localisation of the DES makes the renewable energy technologies favoured options. Renewable energy can be generated through different sources: hydropower, wind, ocean, solar, geothermal and bioenergy. Bioenergy involves production of biofuels: biodiesel, bioethanol and biogas from biomass which could be achieved biologically, thermally or mechanically depending on the nature of the biomass and biofuel type (Wellinger et al., 2013). Substantial quantities of agricultural wastes are being generated within the rural areas which can be used for rural electrification. Depending on the nature of the agricultural waste, the frequently used approaches are gasification and anaerobic digestion. However, while gasification is employed for biogas generation from solid waste (Couto et al. 2016;Chen et al. 2016); anaerobic digestion is often utilised for liquid or solid wastes with high moisture content (Yin et al., 2016). The use of anaerobic digestion (AD) processes in rural area is advantageous for the following reasons summarised in the Table 1-1 (de Mes et al. 2003;Spellman and Whiting, 2007; Nguyen, 2014).

Table 1-1: Advantages of anaerobic digestion process

Energy production	• AD can be used to produce flexible renewable fuel that can be utilised to produce heat and power. • Produced biogas can be used onsite or offsite as transport fuel or grid gas supply. • Can be used to treat the organic fraction of waste and thus increases its calorific value.
Waste management	• Encourages local management of waste in accordance with local waste management policies while reduces carbon foot-printing of waste management. • Allows many streams of wastes to be simultaneously managed through co-digestion e.g. agricultural residue with domestic wastes.
Environmental protection	• Reduces greenhouse gas emission since methane that would have otherwise released into the atmosphere is harnessed and used. • Reduces impact of agricultural activities on the environment. • Encourages production of organic fertiliser and contribute to sustainable nutrient management by closed nutrients cycle. • Reduces over-dependency on synthetic fertiliser
Economic advantage	• Organic fertiliser has been shown to be cheaper than synthetic fertiliser.

To enhance efficiency and reduce cost of bioenergy, the renewable energy source can be utilised simultaneously to generate electricity with heat (CHP) or both heat and cooling (tri-generation otherwise known as Combined Cooling Heat and Power (CCHP) (Guoquan et al., 2011). Thus, because of these benefits, numerous studies have been carried out to evaluate biomass fuelled CHP systems especially technical, economic and policy requirements.

The performance comparison operation of a CCHP in different modes was evaluated by Wang et al. (2011) for a commercial building and a separate external load. The results show that the viability of the CCHP is stringently influenced by the building energy demands. A similar work carried out at different climatic zones which uses thermal demand management (TDM) and electricity demand management (EDM) indicates the dependency of CCHP projects on the onsite energy demand (Jiang-Jiang et al., 2010). The study reveals that the CCHP in TDM mode is most suitable for cold areas while EDM mode is most appropriate for the buildings with constant thermal demand in warm climatic zones. Most of the current power plants are efficiently deficient due to unutilised excess heat (Loeser and Redfern, 2010) especially the low-grade heat. Thus, the mandatory requirements for a feasible CHP/CCHP system is the availability of an onsite electrical and thermal demand. An economic viability of manure-based biogas powered CHP was assessed by Lantz (2012) using different scales of CHP technology in Sweden. The study showed that none of the assessed scale is profitable, as there exist gaps between biogas production cost and the break-even point that may need to be covered by a special policy. Similarly, Huang et al. (2013) evaluated a biomass gasification organic Rankine cycle (ORC) CHP systems using different sources of biomass and load applications. The result indicated that, while the configurations led to improved system efficiency that is biomass specific, the break-even selling point (BESP) varies between 87 and 97 £/MWh which is higher than the prevailing BESP of 40 to 50 £/MWh for the ORC-CHP systems. Hence, a reduced cost of biomass is recommended. More so, a biogas fuelled CHP system where the recovered heat was used for onsite drying of agricultural products was studied by Lamidi et al. (2017b) using Aspen Plus (AP) simulation tools. The configuration reportedly increases the system efficiency from 25.6% to 58.4%. The payback period was 3.2 years with the inclusion of Feed in Tariffs (FITs), but such systems' scale is not currently captured on the Nigerian FITs system since it is less than 1MWe. François et al. (2013) used AP to predict the effect of varying operation parameter on biomass gasification CHP plant. The overall exergetic efficiency of the system was found to be inversely proportional to the moisture content of biomass feedstocks which was tested between 15 -50%. Notwithstanding, while CHP in building and industrial applications have been widely studied, little had been reported on its application to agricultural activities particularly in areas of technical and policies requirements. Its applications as decentralised distributed energy system in this regard have not been fully researched particularly where electricity delivery is combined with basic processing of agricultural products. Hence, in this study, a model of biogas driven poly-generation system is presented. The developed model should use recovered energy from agricultural wastes; be reliable, affordable and able to satisfy cooking, heat and electricity requirements of an agrarian community. Based on biomass availability, a part of the biogas would be used directly for cooking while a part would be used for the CHP unit. The recovered heat from the CHP unit would be used to maintain the AD process, post-harvest crop drying and cool storage of agricultural products. Aspen Plus is very useful for both biochemical and physical processes. Therefore, it would be used for the simulation of AD process, combined cooling, heating and power (CCHP) system, heat recovery for AD system and economic analysis of the model. The overall objective of the study is to, through Nigerian renewable energy policy, carry out a techno-economic evaluation of a small-scale anaerobic digestion biogas driven CCHP system where the recovered heat is used for agricultural products processing. Importantly, the study aims at highlighting the prospects of such configurations in reducing both energy poverty and heavy PHL in the Sub-Saharan African region.

1.2 Aim and objectives

The study aims at synchronising rural electricity delivery with basic post-harvest processing of agricultural products by investigating the potential and feasibility of a Combined Cooling, Heating and Power system driven by locally available biomass resources from the agricultural wastes in the area. Such system is to simultaneously produce electricity as well as heat for drying and cold storage of agricultural produce. The specific objectives are to:

1) Investigate the current energy usage and demand of the farming households in a selected Nigerian rural community.
2) Identify the main agricultural products produced from the community, and the level of post-harvest losses in the area.
3) Identify and investigate the renewable energy resources (agricultural biomass residue) available in the area; carry out a field study and collet the typical wastes samples.
4) Analyse the typical wastes samples and identify the appropriate energy recovery option.
5) Design a biogas driven poly-generation system that can satisfy the required energy demand.
6) Set up computational models of the poly-generation system including: an anaerobic digestion model for production of biogas; a CCHP system for providing drying, heating, cooling and power using Aspen Plus simulation tool.
7) Perform economic evaluation of the system.

1.3 Layout of the thesis

The thesis has been organised into eight chapters and the supporting appendices. The first being the introductory chapter which outlines the aims and the rational for the study. Other chapters are arraigned as follows:

- Chapter 2 presents review of literature pertinent to the objectives of the study which include a combined heat and power system and its application, anaerobic digestion process, principle and simulation, absorption refrigeration system, energy situation and post-harvest loss in Nigeria, anaerobic digestion potential in Nigeria and recent advances in sustainable drying of agricultural products. Details on the working principle of Aspen Plus software was also presented.
- Chapter 3 presents the results of site visit and survey for the estimation of energy required for cooking, drying, cooling and lighting.
- Chapter 4 gives details of the postharvest loss in Nigeria as examined through postharvest handling operations of tomato.
- Chapter 5 discusses details of design and modelling of the system.
- The results of the technical and economic evaluation presented in the form of different scenarios is presented in Chapter 6.
- Summaries of the study, limitations of its applicability and future recommendations are discussed in Chapter 7.

Chapter 2 : Literature Review

2.0 Introduction

The objectives and rationale behind this study were discussed in the last chapter. As mentioned, the overall aim of the study is to address both energy poverty and prevalence of heavy postharvest loss in Sub-Saharan region through farm residue fuelled combined heat and power system. It is to be x-rayed in context of a Nigerian village as this is thought to reflect the aforesaid challenges in many countries within the region. Over the last few decades, lots of researches on the combined cooling, heating and power generation systems otherwise known as tri-generation had been reported. Its principle, choice of mover, optimisation, economy and applications in various forms have widely been researched. Many studies had also been conducted both on energy situation and the current heavy postharvest loss in sub-Saharan Africa region and Nigeria in particular. Hence, in this chapter, a full review of the literature pertinent to the aforementioned objectives will be extensively discussed. The review starts with the principle of the Combine Heat and Power (CHP) systems, tri-generation and its applications. The choice of prime mower is then discussed. This will be followed by the review of the thermodynamics of gas engines. A short review covering energy and postharvest loss situation in Nigeria is presented. Anaerobic digestion principles, operating conditions, its potentials and challenges in Nigeria is highlighted. Then, overview of absorption refrigeration system is discussed. Besides, rationale for the choice of Aspen Plus software for the simulation of anaerobic digestion process, mower and drying unit is elaborate Finally, mechanism of drying and approach to sustainable drying of agricultural product is discussed.

Nigeria is among the world’s poorest energy countries. World Bank, (2018) reports that the per capital electricity consumption in Nigeria was 144 kWh in 2016 while that of the United States and United Kingdom were 12,984 kWh and 5,130 kWh respectively. The installed electricity capacity is around 7000MW while demand is around 12,390MW. Electricity generation rarely exceeds 4000MW (Ishola et al., 2013; Adaramola et al., 2014). Nigeria’s electricity loss of around 30-35%, due to distribution and transmission, is among the highest in the world which is ascribed to obsolete equipment and poor maintenance (Oseni, 2011). Consequently, only 48% of the households is connected to the national grid. Grid connection is around 60-70% in urban areas while as low as 25% of the rural communities are connected. Power outage between 6-15 hours per day is frequently being experienced by the grid connected consumers (Visser et al., 2016) and this has necessitated backups by domestic and enterprise consumers. Importantly, these backups which is mainly diesel and gasoline powered generators is currently around 700,000 units generating about 6000MW at between \$0.50 to \$0.75/kWh (Newsom, 2012) which is more than the current \$0.0200/kWh and \$0.0615/kWh for consumers classified as R1 and R2 respectively (Nigerian Electricity Regulation Commission, 2012).

More so, the existing transmission capability is below 6000MW and the cost of grid extension is high fluctuating between \$25,000 to \$100,000/km depending on location (Adaramola et al., 2014). The Transmission Company of Nigeria which is responsible for the management of both 330- and 132-kW transmission structure is confronted with damaged grid as a result of insufficient maintenance and financing. At the moment, the existing grid infrastructure cannot take the available generation due to the dawdling expansion of the transmission systems in relation with the speedy expansion of the generation facilities (Ohiare, 2014). Therefore, power generation system that depend on decentralised mini-grids and/or small scale off-grid distribution systems is being explored to improve the present level of electricity access in Nigeria particularly in the rural areas.

2.1 Combined Heat and Power Systems

Combined heat and power (CHP) (Figure 2-1) is the simultaneous generation of electricity and heat from a single engine. The capacity varies from few watts to several megawatts. However, the mini CHP, which is the focus of this study is a system between 25 and 500 kWe (Pellegrino et al., 2015). Conventional power system converts about 30% of the fuel input to electricity while the remaining fuel energy is lost as waste heat (Ajav et al., 2000). CHP systems also called cogeneration recover waste heat into useful heat which are sometimes used onsite or within the neighbouring district heating systems. The recovered heat is used as process heat or used by thermally driven cooling systems such as absorption or adsorption chillers for space cooling. When this is incorporated to a CHP system, it becomes combined cooling, heat and power (CCHP) or tri-generation plant (Wiser et al., 2010).

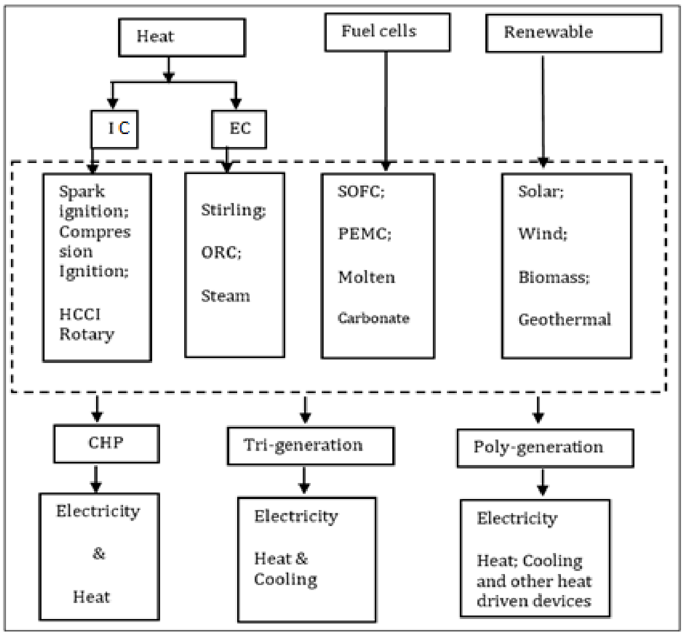


Figure 2-1: Multi-generation flow chart (adapted from (Murugan and Horák, 2016)*).*

When this is integrated, the overall efficiency of the system can be between 75% and 85% depending on the prime mover used (Ibid). Besides, CHP system is environmentally friendly as most micro-generation systems are either powered by natural gas, renewable fuels or renewable technologies such as concentrated solar panel. More so, loses due to transmission and distribution of electricity are minimised with the use of CHP as the energy is produce and utilised onsite or near site (Cho et al., 2014). The global capacity of CHP systems is valued at around 330 GWe. Notwithstanding, the choice of prime mover is critical to the success of the CHP systems and its overall optimisation in terms of cost and energy efficiency strongly depends on the choice of movers (Department of Energy and Climate Change, 2008) coupled with the site's heat and electricity demand. This is because operation conditions and heat recovery to electricity ratio differs among prime movers. Consequently, the characteristics of prime movers is presented in the Table 2-1. From the table, it can be observed that fuel cell has highest electrical efficiency, not noisy and low emission. However, it may not be appropriate where high thermal demand is required for the CHP system. Besides, it requires high level of fuel cleaning and its frequency of maintenance is very high. These increases both initial capital and operational costs. The requirements of specialised maintenance also make its adoption for rural system challenging as this might impact the overall availability of the system. Gas turbine has high thermal efficiency and it is suitable for CHP systems with high thermal load. It is not as noisy as gas engine but has lower electrical efficiency compare to gas engines. Its frequency of maintenance is not as much as fuel cell. However, it also requires cleaner fuel and specialised maintenance. Again, this may be challenging for rural applications. On the other hand, gas engine is noisy and has high emission. However, its electrical efficiency is better than gas turbine while thermal efficiency is almost equal. It can work effectively with poor oil, has longest period of overhaul and does not require specialised maintenance. These features of gas engine make it suitable for rural applications.

Table 2-1: Characteristics of CHP prime movers

Particulars	**Gas Engine**	**Gas turbine**	**Fuel cell**
Electrical efficiency (%)	30-38	26-34	40-45
Thermal efficiency (%)	41-49	40-52	30-40
Noise	Noisy	Less than gas engine	Not noisy
Emission	High emission	Cleaner than gas engines	Low emission
Fuel requirement	Accept poor oil	Cleaned fuel required	Extreme fuel cleaning required
Maintenance	No specialised maintenance	Specialised maintenance	Specialised maintenance required
Fuel pressure	Low pressured fuel (3-5psig)	High pressure (100-400psig)	High pressure (100-400psig)
Overhaul frequency (hr)	28,000-90,000	30,000-50,000	10,000-40,000
Ambient condition	Unaffected by ambient temperature	Efficient varies with ambient temperature	Efficient varies with ambient temperature

Adapted from (Wiser et al. 2010; Department of Energy and Climate Change, 2008)

Therefore, based on the features presented above, gas engine is chosen as prime mover for this study. Its choice is based on high electrical and thermal efficiency couple with non-requirement of specialised maintenance which is suitable for rural area applications. Importantly, diesel and gasoline powered vehicles and generating sets are popular in Nigeria. Thus, getting a maintenance engineer in any part of the country may not be difficult.

2.1.1 Thermodynamics of gas engine

A gas engine is an open cycle internal combustion engine (ICE) where combustion occurs in the working fluids (air and fuel). It operates on Otto cycle (Figure 2-2) which assumes that all energy from the fuel is utilised in the engine. The cycle describes the effects of changing in pressure, temperature and volume in addition to heat rejection or addition to a mass of gas (Winterbone, 2015). The system assumes both isentropic and isochoric process.

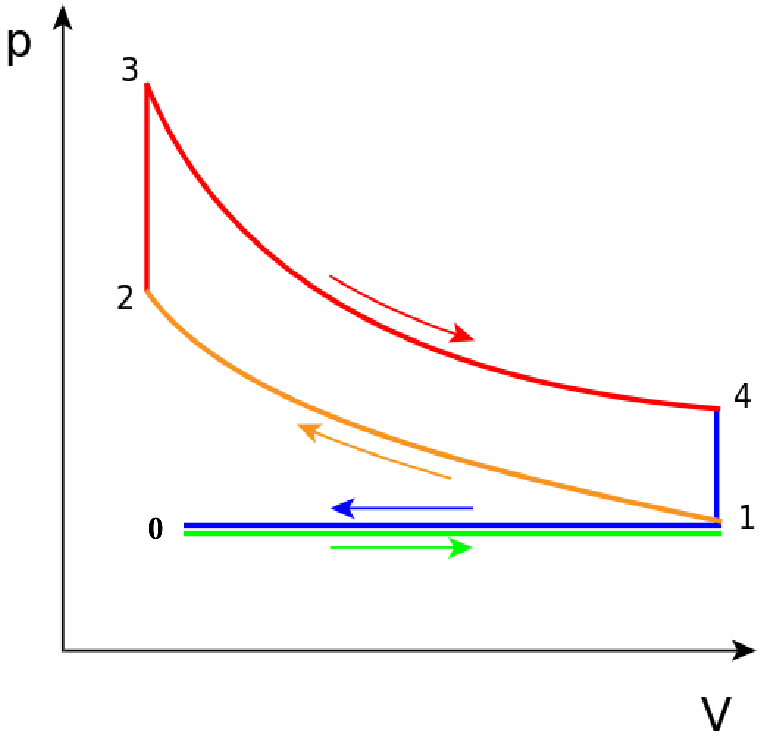


Figure 2-2: Otto cycle (Adapted from Winterbone, (2015)

An Otto process is described as follow:

I. Route 0-1 known quantity of air is drawn into the cylinder at constant pressure.
II. Route 1-2 isentropic compression of air while piston travels from bottom to the top.
III. Route 2-3 constant volume ignition of fuel-air fluid leading to transfer of heat to the fluids.

IV. Route 3-4 isentropic expansion/power stroke

V. Route 4-1 completes the cycle at constant volume heat rejection while piston is at the bottom of the cylinder.

Assuming all energy from the fuel is utilized in the engine and both kinetic and potential energies are negligible, from first law of thermodynamics the energy balance of an Otto cycle could be presented as in equation 2.1:

$$D_e = E_{in} - E_{out} = 0 \qquad (2.1)$$

Where D_e is the change in internal energy and E_{in} and E_{out} represent energy into and out of the system respectively. Thus, from Figure 2.1, routes 1, 2, 3 symbolise energy into the system while processes 3, 4, 1 signify energy out of the system.

2.1.2 Energy balance of an internal combustion engine

Numerous works (Ajav et al., 2000; Abedin et al., 2013; Yingjian et al., 2014) had been reported on the energy balance of an internal combustion engine (ICE). The most frequently used approaches are experimental and modelling. In both cases, an ICE is regarded as a thermodynamic open system or control system (Figure 2-3) such that mass and energy inflow and outflow can be visualised. In this case, fuel and air are input to the engine while break power and heat loss through the exhaust, cooling medium, convection and radiation are the output from the system.

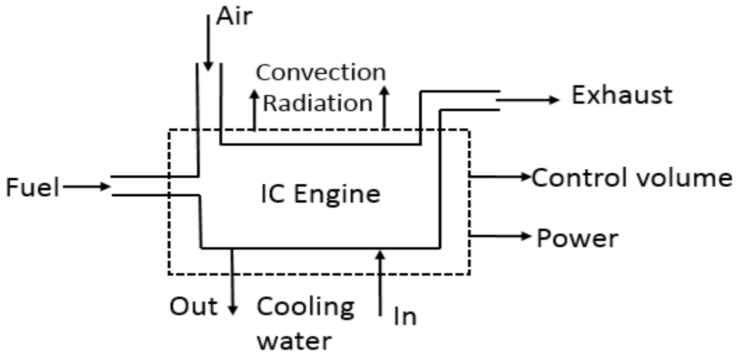


Figure 2-3: Control volume of an ICE showing energy flow (Abedin et al., 2013)

The first law energy balance of the system will be (equation 2.2):

$$Q_s = P_b + Q_{cm} + Q_{exh} + Q_{misc} \qquad (2.2)$$

Where Q$_s$, P_b, Q_{cm}, Q_{exh} and Q_{misc} symbolise heat supplied by the fuel, brake power, heat rejection to the cooling medium, exhaust heat loss and the miscellaneous heat loss to the surrounding through radiation and convection (Abedin et al. 2013; Ajav et al. 2000).

Heat supplied by the fuel Q_s can be evaluated as:

$$Q_s = M_f * Q_{LHV} \qquad (2.3)$$

Where $\mathrm{M_f}$ is the mass flow rate of fuel (kg/hr) and $\mathrm{Q_{LHV}}$ is the low heat value of the fuel in kJ/kg and $\mathrm{Q_s}$ is the heat supplied (kJ/hr) by the fuel.

The brake power (P$_b$) is the useful work produced by the engine and can be calculated as (2.4)

$$P_b = 2\pi NT * \ 10^{-3} \qquad (2.4)$$

Where N is the frequency of the engine in (rev/sec) and T is the torque in NM.

Heat rejection to the cooling medium $\mathrm{Q_w}$ can be estimated from the equation (2.5).

$$Q_{cm} = M_{cm} * C_p * \Delta T_{cm} \qquad (2.5)$$

Where $\mathrm{M_{cm}, C_p, \Delta T_{cm}}$ means mass flow rates of cooling medium, specific heat capacity and change in temperature of the cooling medium.

Heat loss through exhaust can be found through equation 2.6.

$$Q_{exh} = \left(M_f + M_a\right) * C_g * \ \left(T_g - T_a\right) \qquad (2.6)$$

Where M_f, M_a, C_g, T_g and T$_a$ signify mass flow rates of fuel, mass flow rates of combustion air, specific heat capacity of the exhaust air, temperature of exhaust air and ambient air temperature respectively.

The miscellaneous heat loss to the environment can be estimated by subtracting summation of equations 2.4;2.5 and 2.6 from equation 2.2 (Rakopoulos and Giakoumis, 2006). Using the aforesaid principle, both experimental and modelling approaches can be adopted to carry out the parametric study of an ICE. With an ICE assumes as a thermodynamic control volume, effects of changing parameters such as changing atmospheric condition, air-fuel ratio, compression ratio, fuel purification etc. on both electrical and thermal performances of the engine can be evaluated.

The effects of different blends of diesel and ethanol fuels on the thermal balance of an ICE was investigated by Ajav et al. (2000). The results show that thermal efficiency of the engine was not significantly difference at 5-10% ethanol blends whereas a considerable difference in the thermal efficiency was observed at 15 and 20% ethanol-diesel blends. More so, the experimental study of a pre-commercial natural gas (NG) fuelled 5 kWe micro CHP which uses oil jacket as the only cooling system was investigated by De Santoli et al., (2015) using blends of hydrogen-NG. The study recorded a 2.28% increase in electrical efficiency when 15% hydrogen is blend with NG. The increased electrical efficiency is attributed to an enhanced fuel combustion which increases the mechanical efficiency of the engine. Expectedly, a reduction in the heat recovery efficiency of the engine was recorded. The observed reduction in heat recovery efficiency became worst when engine load is lower than 58% but insignificant above 70% engine load. This phenomenon was attributed to the increased mechanical efficiency which reduces thermodynamic losses. Similarly, using wet ethanol (5,10,20,30,40% water) Ambrós et al. (2015) performed both modelling and experimental study of an ICE. The study evaluated the effect of fuel compositions on brake power, torque, efficiency, specific fuel consumption and exhaust gas temperature and suggests that the modelling, which was done using MATLAB to solve thermodynamic equations, agreed with experimental results with an average deviation of 7%. Wet ethanol of 30% water composition reportedly shows best result but with increased specific fuel consumption.

2.1.3 Economic and technical evaluation of CHP

CHP systems are often evaluated technically, economically, and environmentally. While either of these can be used to appraise a project's viability, a multi-criteria approach can be adopted for decision making (Jiang-Jiang et al., 2010). The technical evaluation, among other things, often look at the system's efficiency, process optimisation, sizing and feedstock availability (biomass CHP) while economic indices (the net present value, leverage cost of electricity, profitability index, payback periods etc.), sensitivity analysis, grant, policies and incentives availability are tools often used for the economic evaluation (Wiser et al., 2010). Besides, the environmental evaluation is often based on CO_2 production and footprints. As a rule of thumb, the requisite requirements for a feasible CHP/CCHP system is the availability of an onsite or near-site electrical and thermal demand. Hence, the frequently adopted management approaches (Jiang-Jiang et al., 2010) to CHP systems are the thermal demand management (TDM) and electricity demand management (EDM). The performance comparison operation of a CCHP in different modes was evaluated by Wang et al. (2011) for a commercial building and a separated external load. The results show that the viability of the CCHP is stringently influenced by the building energy demands. A similar work carried out at different climatic zones which uses thermal demand management (TDM) and electricity demand management (EDM) indicates the dependency of the CCHP systems on the onsite energy demand (Jiang-Jiang et al., 2010). The study reveals that the CCHP in TDM mode is most suitable for cold areas while EDM mode is most appropriate for the buildings with constant thermal demand in warm climatic zones. Thus, unutilised excess heat has been recognised as the reason behind inefficient of the most currently installed CHP units (Loeser and Redfern, 2010; Jiang et al., 2017).

Soltani et al. (2015) studied a biomass sawdust fuelled multi-generation CHP system. The energy and exergy efficiency of the system reaches 60% and 25% respectively especially when applying deaerator as against simple heat exchanger for district heating needs. The use of the deaerator increases mass flow rate of hot water by 10%. Besides, a laboratory investigation of a tri-generation system was carried out by Fu et al. (2009) where desiccant dehumidifier was used in addition to chillers and the authors conclude that the overall efficiency of the system is a function of the extent and mode of heat recovery particularly the low quality heat. Importantly, a cost effective CHP system could be optimally achieved using thermodynamics principles where the systems working fluids and operating conditions are modelled (T.T. Al-Shemmeri, 2011). In this way, the effects of varying demand of heat and electricity on the performance parameters and the overall utilisation factors of power to heat ratio can be evaluated. Fundamentally, a CHP project could be technically feasible and not economically feasible and vice versa (Wood and Rowley, 2011). Accordingly, the decision making is often traditionally based on, at least, the combination of the technical and economic feasibility of a project. For instance, using ECLIPSE software for the simulation, the techno-economic evaluation of two biomass fuelled 150 kWe Organic Rankine cycle and gasification CHP for commercial building in the UK was designed and analysed by Huang et al. (2013). The overall energy efficiency of the system was reported to be 76% and 81% for willow chip and miscanthus respectively while the break-even selling point (BESP) varies between 87 and 97 £/MWh which is higher than the prevailing BESP of 40 to 50 £/MWh for the ORC-CHP systems. Hence, a reduced cost of biomass is recommended. More so, a biogas fuelled CHP system where the recovered heat was used for onsite drying of agricultural products was studied by Lamidi et al. (2017b) using Aspen Plus (AP) simulation tools. The configuration reportedly increases the system efficiency from 25.6% to 58.4%. The payback period was 3.2 years with the inclusion of Feed in tariffs (FITs) but such systems' scale is not currently captured on the Nigerian FITs system since it is less than 1MWe.

More so, the viability of a renewable energy (RE) project strongly depends on changes in policy, regulation, the financial market and the price volatility of fossil fuels (Wright et al., 2014). For instance, the economic performance of a biogas fuelled CHP system in Sweden was investigated by Lantz, (2012) and using both mesophilic and thermophilic approach on small to large scale plants, the finding reveals that, given the present policy, the project is not economically feasible. This is because the existing policy does not bridge the gap between biogas production cost and the breakeven cost. Furthermore, Pellegrino et al. (2015) investigate the techno-economic and policy requirements for the commercialisation of micro scale solid fuel cell CHP systems with respect to residential buildings in Italy and UK and they conclude that the current retail price is 4 to 5 times higher even with the current Feed in Tariffs of the UK. Thus, special incentives were proposed for the fuel cell CHP system. More so, a hybrid solar gas fired CCHP system was investigated with the climate of north-western region of China (Zhai et al., 2009). Using exergy and energy analysis approach, the study suggests that the solar conversion efficiency of the hybrid system can be increased from 10.2% to 58% while exergy is increased from 15.2% to 12.5%. However, the calculated value of payback period of 18 years was not economical and a reduction of interest rate to 3% was suggested. Summary of some recent works on CHP evaluation is presented in the Table 2-2

Table 2-2: Recent works on evaluation CHP/ tri-generation.

N	Author (s)	Studies	Findings
1	Huang et al. (2013)	Biomass ORC-CHP and Gasification CHP in commercial building using ECLIPSE software.	The overall CHP efficiency is biomass dependent with 76% and 81% respectively reported for willow chips and miscanthus. The differences are associated with the differences in biomass moisture content. Biomass ORC-CHP was 30-

			40% more efficient than gasification CHP and the break-even point was halved.
2	Wright et al. (2014)	Barrier and techno-economic analysis of small-scale biomass CHP schemes in UK (case study)	Capital structuring, feedstock type and price uncertainty and plant oversizing responsible for the failure of the case studies
3	(Wood and Rowley, 2011)	Biomass-fuelled CHP for community housing in context of energy services company.	Positive net present value demonstrated without capital subsidies but subject to optimal system design and implementation at high load factors when the maximum quantity of both electricity and heat sold on-site is maximised.
4	Lythcke-Jørgensen et al. (2014)	Exergy analysis of a poly-generated CHP plant with integrated lignocellulosic ethanol production and district heating.	Exergy efficiency of the varied from 0.564 to 0.855. The highest was obtained for integrated operation at reduced CHP load and full district heating production.
5	Yingjian et al. (2014)	Energy balance and efficiency analysis for power generation in ICE sets using biogas from beer waste water (Case study)	The efficiency of the system could be increased from the present 28.45% to 80% if wasted heat is recovered.
6	Pellegrino et al. (2015)	Policy requirements for the market-entry of the fuel cell micro-CHP system (Case study)	Retail prices of €2,500 and €650 were respectively found for families

			consuming 9,000 and 3,500 kWh/annum. These prices are 4-7 times higher than the current UK prices even with FITs. A special FITs would be required for fuel cell CHP.
7	Fu et al. (2009)	Laboratory investigation of different configurations of CCHP with respect to residential sector	The overall system's efficiency and operating parameters depend on configurations which can be as high as 90%. Hence, configurations play major role in determine the efficiency of CCHP system.
8	Soltani et al.(2015)	Thermodynamic analysis of a novel multi-generation sawdust biomass CHP.	Applying a dehydrator as against simple heat exchanger in district heating result in 10% more hot water flow and the overall efficiency of the system increase to 60% from 11%.
9	Samadi et al. (2014)	CHP technology for drying of agricultural products.	Highest system efficiency recorded at 75% engine load.
10	Mel et al. (2015)	Biogas powered CHP	The AD process margin is achieved at 11% and rate of return on investment is 12% which gives a payback period of 8.2 years.

2.2 Biomass and bioenergy

Biomass are biological materials living or recently living organism which are either directly from plant or plant-derived materials (Helwig et al., 2002). It can be broadly categorised into agricultural (crop residues), forestry (tree cuttings, sawmill and paper waste), aquatic (water hyacinth), waste biomass (municipal solid waste, industrial waste, human and animal excreta). The continuous global demand for energy, finitude of fossil fuels and concern for environment had necessitated an increased demand for the biomass-based renewable energy sources (Guoquan et al., 2011). Bioenergy or biofuel could be solid (firewood, charcoal), liquid (biodiesel, ethanol) or gas (biogas, flue gas, and syngas). It is usually obtained from biomass materials by thermochemical methods such as combustion, gasification or pyrolysis or through biological degradation using aerobic or anaerobic digestion. However, of interest to this study is biogas from anaerobic digestion. This is partly due to the availability of agricultural residue in rural areas as well as suitability of digestate for organic fertiliser.

2.2.1 Anaerobic digestion overview

Anaerobic digestion (AD) involves the breakdown of biodegradable material in the absence of oxygen by micro-organisms to produce digestate (a nitrogen rich fertilizer) and biogas which is a mixture of methane (45-75%) and CO_2 (25-55%) depending on the feedstock and processes used (Ngumah et al., 2013). In addition to CO_2 and methane gas produced, impurities such as hydrogen sulphide, carbon monoxide, ammonia and other gases are also produced (Lindorfer et al., 2006). The produced biogas can be used to generate electricity and heat to power on-site equipment while the excess electricity can be transferred to the national grid. It can be burned to produce heat, or can be cleaned and used in the same way as natural gas or as a vehicle fuel (DEFRA, 2011). At the domestic scale, it can be used for cooking, lighting and heating. The advantage of AD over other renewable energy technologies such as solar and wind lies on its non-intermittency. However, it success solely depends on availability of substrates.

2.2.2 Principles of anaerobic digestion

AD is a redox reaction which involves breaking down of biodegradable or organic matter in the absence of electron acceptor such as oxygen. In this case, the organic carbon is respectively converted to its most stable oxidized (CO_2) and reduced (CH_4) state (Angelidaki and Sanders, 2004). In addition to the main products which are CO_2 and CH_4, small quantities of nitrogen, nitrogen dioxide, hydrogen sulphide, hydrogen and ammonia are also produced which usually account for less than 1% of the total volume of the gas produced. The conversion process involves series of reactions which are as illustrated in the Figure 2-4. The process takes place in 3 stages: hydrolysis, acidogenesis and methanogenesis. The organic material is disintegrated into carbohydrates, lipids, and protein which are subsequently hydrolysed, by the extracellular hydrolytic enzyme, into long chain fatty acids, short chain carbohydrates and amino acids (Lauwers et al., 2013). The hydrolytic enzymes are released by the microorganisms which are in the bulk of liquid or attached to the surface of the particles. Thereafter, acidogenic microorganisms change these soluble compounds into alcohol and organic acids such as acetate, propionate, butyrate and valerate. These soluble compounds are subsequently converted to acetate and ultimately to methane and carbon-dioxide by acetoclastic methanogens. The intermediate carbon-dioxide and hydrogen are also combined via hydrogenotrophic methanogens to generate CH_4 and this later process is responsible for about 30% of methane production. Importantly, optimisation and composition of biogas is a function of factors such as substrate composition, pre-treatment, temperature, pH, retention time, the reactor type etc.

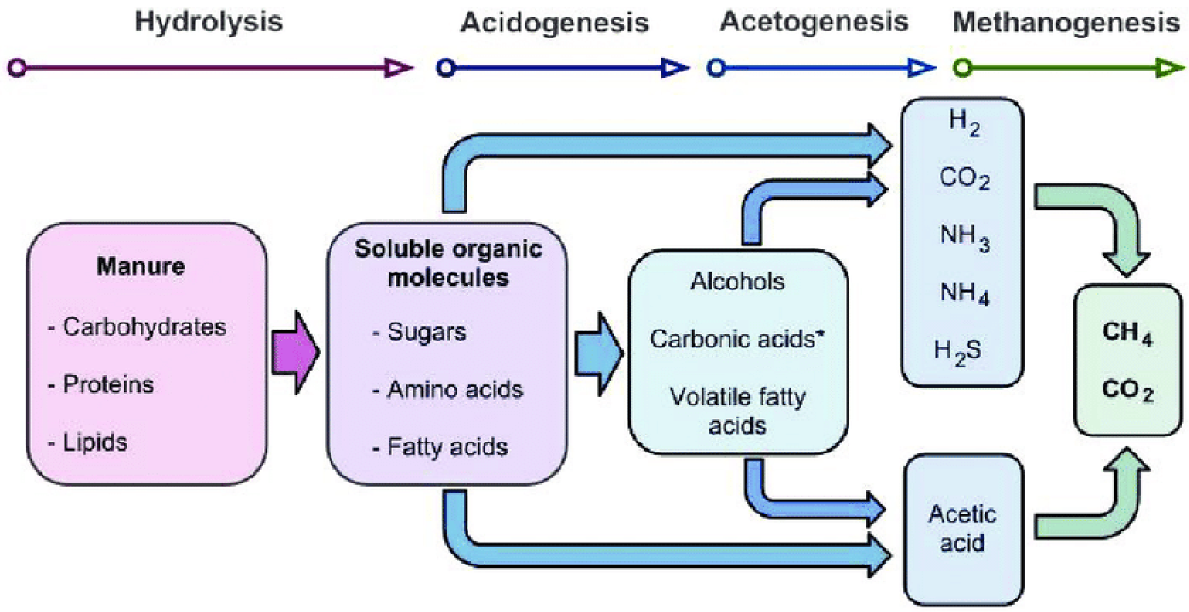


Figure 2-4: Overview of the schematic AD process (Milićević et al., 2017)

2.2.2.1 Substrate composition

Biogas composition, quality and quantity is a function of the substrate's structure. The yields depends on the content of the organic compounds such as protein, fats and carbohydrates which are the only biologically degradable constituents of the biomass feedstock under AD conditions (Zhang et al., 2007). Habig, (1985) determines the influences of substrate composition on biogas yields and reports that carbohydrate and protein contents of substrates determines its biogas yield. Besides, Dandikas et al. (2014) also examined the relationship between biogas yield and chemical structure of energy crops and noted that the acid detergent lignin and hemicellulose composition are the major factors in estimating biogas yields of plants. Classification of AD system can be done on the bases of the total solids (TS) of the substrates which subsequently determine pre-treatment methods and the choice of reactor. Low solids reactor (LS) contain less than 10 % TS, medium solids (MS) contain about 15%-20%, and high solids (HS) processes range from 22% to 40%.

2.2.2.2 Temperature

Temperature changes the overall kinetics of the system and solubility of gases. The growth, survival, and metabolic activities of microorganisms are greatly influenced by temperature (Angelidaki and W. Sanders, 2004). Thus, temperature is an important factor in controlling the metabolic activities of microorganisms. The three different temperature under which AD is commonly carried out are: psychrophilic (<20^{0}C), mesophilic (25-40^{0}C) and thermophilic (45-60^{0}C). Generally, process rates twofold for every 1^{0}C rise in temperature (Kranert et al., 2012) until highest temperature of 60^{0}C is reached after which process rates drop as the metabolic activities of the microbes are compromised. Thermodynamically, hydrogenotropic methanogenesis reaction preferred less temperature while higher temperature is desirable to the acetoclastic methanogens (Appels et al., 2008) and this explains while two stages reactors are sometimes preferred for system optimisation. Importantly, reactor temperature changes of more than 1^{0}C per day can result in process failure. Thus, changes in temperature of more than 0.6^{0}C/day should be avoided especially in thermophilic process (ibid).

2.2.2.3 Pre-treatment

AD feeds are usually sourced from different sources: farm waste, restaurant, industrial and domestic waste. Hence, it is not only commonly heterogeneous but also comes in larger sizes that need to be broken to increase the surface area for microbial activities (Seppälä et al. 2008; Bochmann and Montgomery, 2013). Pre-treatment systems are built on three principles: physical (mechanical shear, heat, pressure and electric fields), chemical (acids, bases and solvents) and biological (microbial and enzymatic). Sometimes, more than one principles are combined to increase biogas yield. Combinations of these principles are also used, including steam explosion, extrusion and thermo-chemical processes. Numerous studies, (Kratky and Jirout, 2015; Aslanzadeh et al., 2011; Yin et al., 2016; Li et al., 2009), conducted on the effects of pre-treatment on biogas yield indicate between 40 to 250% increase in biogas yield related to the substrates pre-treatments. Hence, considering the profound effects of pre-treatments on both biogas and methane yield, details of its approaches are presented below:

Hydrolysis is a rate-limiting process in the anaerobic digestion system. Hence, pre-treatment which can be defined as any process that converts biomass feedstocks into a form which enhances enzymatic hydrolysis is often recommended for the AD process. The essence of pre-treatment is to produce a disrupted, moistened substrate that is easily hydrolysable and devoid of sugar degradation in addition to fermentation inhibitors. With pre-treatment, both rates and extent of anaerobic digestion can be enhanced. It has also been associated with increased biochemical methane potential (BMP).

Depending on the source, the feedstock is generally characterised as lignocellulosic biomass (grass silage, crop residue, manure, and energy crops), sewage sludge, animal by-products, food wastes and the organic fraction of the municipal solid wastes (OFMSW). Pre-treatment (PT) can be carried out using thermal, thermos-chemical, chemical, mechanical, and biological methods (Jain et al., 2015). Therefore, the choice of the pre-treatment method is influenced both by the type of feedstock and the targeted outcome of pre-treatment. For instance, rather than improved BMP, pre-treatment is adopted in sewage sludge to reduce bulkiness and retention time (Valo et al., 2004) while its adoption in animal by-products is for the sanitation purposes (Carrere et al., 2016).

Mechanical pre-treatment of feedstock can be achieved through shredding, sonification, centrifugation, lysing, electroporation and high pressure. Shredding is one of the most widely used PT methods and it involves the reduction of particle sizes, which increases the surface area of biomass and make it accessible to enzymatic hydrolysis. The effect of mechanical disintegration of feedstock on AD performance of a full-scale (800m^3) straw-based horse manure was investigated by Mönch-Tegeder et al. (2014). Feedstock involving horse manure, grain silage, maize silage, grass silage, and crushed grain were ground before co-digested at 40ºC at 79±16 d and 2.9±0.5 kg VS/m^{3}d hydraulic retention time and organic loading rate respectively. Similarly, a 40% increase in chemical oxygen demand (COD) solubilisation was observed by Izumi et al. (2010) after grinding food waste feedstock with bead milling. The result also suggests that the pre-treatment led to a 28% higher biogas production. However, excessive size reduction could result in lower biogas production (Jain et al., 2015) while the choice of some size reduction methods such as screw press can lead to high loss of biodegradable materials (Taherzadeh and Karimi, 2008). More so, Zeynali et al. (2017) used 20 kHz and 80 μm operated at three sonication times: 9, 18, 27 min to examined the effect ultrasonic pre-treatment on both biogas yield and specific energy consumption of AD of fruit and vegetable wastes. The result indicated that ultrasonic PT reduces the HRT from 25 days to 12 days for treated and untreated samples respectively. Besides, the highest methane yields were obtained at 18 minutes while longer sonification period resulted in reduced biogas yield. Similar study conducted by Martín et al. (2015) reported a 95% increase in methane yield from 88 to 172 mL_{STP}/g VS for sonication pre-treated sewage sludge. Notwithstanding the advantages of mechanical PT, it is high energy intensive (usually above 9% of total biogas production) which limits the economy of its deployment (Carrere et al., 2016).

Many studies indicated that thermal PT is an efficient method of increasing methane yield and biodegradability of feedstock for the AD process. A low temperature of 50-70ºC for 10-24 hours or high temperature from 160-190ºC for 20-30 minutes are mostly reported in the literature (Ariunbaatar et al., 2014; Aslanzadeh et al., 2011; Kratky and Jirout, 2015). Ahring et al. (2015) investigated the effect of oxygen aided wet explosion on biogas production of cattle feedlot manure. The substrate was subjected to a wet explosion at 170°C for 25 minutes with 4 bar oxygen. Result suggested that the pre-treatment led to a 357.12% increase in methane production. Besides, anaerobic conversion of lignin content reportedly increased by 31.8% for the pre-treated feedstock. Similarly, Lisbet et al (2015) pre-treated sugarcane press mud with liquid hot water (150°C for 20 min) and the study suggest a 63% increase in methane yield. However, lower methane yield was obtained at temperature above 200°C even at shorter retention time which was attributed to the formation of heat resistant compounds through Millard reaction. More so, hotel food waste was subjected to thermal pre-treatment (60, 80, and 100°C for 10 and 20 minutes). The result indicated a 41% increase in methane production at 100°C for 10 minutes (Gandhi et al., 2018). However, threshold of thermal treatment of feedstock for anaerobic digestion is substrate specific. This is because excessive exposure of substrate to thermal treatment can lead to deterioration of fermentable sugars and production of AD inhibitors (Kastner et al., 2012) which consequently affect biogas production. Liu et al. (2016) studied the effects of thermal PT on co-digested kitchen waste, vegetable waste, and waste activated sludge at 175°C for 1 hour. The treatment led to improved COD and dissolution of sugar and protein. However, there was a 7.9% and 11.7%

reduction in methane yield for kitchen waste and vegetable waste respectively. Also, a similar thermal PT for pig manure, cow manure, fruit/vegetable waste, food waste, and sewage sludge reported a 7.5% and 3.4% reduction in both methane yield and biogas production for food waste (Qiao et al., 2011). There is need to maintain a balance between efficiency enhancement and operational cost. However, some of the challenges of thermal PT are high energy demand and high cost of operation (Amin et al., 2017).

Chemicals including both acids, alkali, and oxidatives are sometimes used for the treatment of feedstock for anaerobic digestion and they have been found to significantly led to increase solubilisation of COD. They are frequently aimed at improving the overall digestibility and do not precisely target a particular composite of the substrate matrix (Wagner et al., 2018). Addition of alkali to biomass results in swelling, reduction of the extent of polymerisation and damaging of bond between lignin and other polymers. It is particularly suitable for low lignin biomass (Badiei et al., 2014) while sodium hydroxide (NaOH), potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$) are the frequently used chemicals for alkali pre-treatments. Compared to untreated feedstocks, a 2.5% KOH-treated corn straw (Jaffar et al., 2016), 6.5% NaOH-treated corn straw (Zheng et al., 2009) and 2.5% $Ca(OH)_2$ -treated corn straw (Li et al., 2015) reportedly lead to a 95.6%, 73.4% and 39.7% increase in methane yield respectively. Acidic compounds such as hydrochloric acid and sulphuric acid have also been reported to improve both biogas and bioethanol production from organic materials. Compare to other methods, acid PT is particularly advantageous due to its ability to disrupt lignocellulosic matrix and conversion of amphous cellulose (Amin et al., 2017). The frequently adopted approaches to acid PT are either a) concentrated acid ((30–70%), low temperature (<100°C) or short retention time (<72 hours); or b) diluted acid (0.1–10%) at high temperature (100-250^{0}C) or long retention time (> 3 days) (Baruah et al., 2018). Song et al. (2014) pre-treated rice straw with different chemical: 2% HCL, 2% H_2SO4 and 4% CH_2COOH for 7 days and the study indicated specific methane yield of 175.6; 163.4 and 145.1 mL/gVS for HCL, H_2SO4 and CH_2COOH respectively, which, compared to untreated sample, resulted in 74.5, 62.4 and 44.2% increase in methane yield respectively. However, drawbacks of acid pre-treatment of biomass are inhibition of subsequent AD processes, corrosiveness and high cost of handling (Amin et al., 2017; Baruah et al., 2018; Song et al., 2014).

Enhanced production of biogas and methane yield has also been reported through adoption of biological pre-treatment of feedstock. Yuan et al. (2011) investigated microbial pre-treatment of corn stalk using composite microbes (XDC-2). Compared to the untreated feedstock, the result indicated a 68.3% and 87.9% increase in biogas and methane yield respectively. More so, a 35.7% reduction in digestion time was also recorded. Similarly, Zhong et al. (2011) adopted a compound microbial agent (0.01% w/w) dose for PT of corn straw at $20^{o}C$ for 15 days. The results showed a 33.07% increase in biogas yield and 34.6% reduction in digestion time. These disadvantages couple with consumption of a fraction of feedstock's carbohydrate by the microbes reduces suitability of the biological processes for industrial pre-treatments of biomass.

Hence, to reduce the inefficiency associated with mono-pretreatment options discussed above, a combination of size reduction (shredding), thermal treatment (70°C for 1 hr) and the use of a local form of sodium carbonate (trona) is suggested. These combinations have been said to enhance biogas generation by around 40% (Egwu, 2019).

2.2.2.4 pH

The microbial activities of AD system is very sensitive to change in pH. Usually, a pH of 6.0 -8.3 is desirable below or above which the microbial activities will be impaired (Angelidaki and W. Sanders, 2004). Fluctuation of pH during digestion process has been attributed to production of alkalinity, volatile fatty acid (VFA), the quantity of CO_2 production (Kondusamy and Kalamdhad, 2014). Production of VFAs during AD tend to lower pH. However, this tendency is usually countered by the activities of methanogenic bacteria which produces alkalinity in the form of CO_2, ammonia and bicarbonate.(Pramanik et al., 2019). Therefore, obtain a stable AD process, it is necessary to control the relationship between VFA and HCO_3 concentrations and a minimum molar ratio of 1.4:1 of HCO_3/VFA has been suggested (Appels et al., 2008).

In their study, Okeh et al. (2014) exposed rice husks produced from different rice mills in Ebonyi State Nigeria to, among other factors, varying pH from 4 to 10. The result indicated the highest biogas production at 7. Besides, a pH increase from 5 to 7 correspondingly led to a COD (chemical oxygen demand) removal efficiency from 50 to 80% for a piggery waste water treatment (Jung et al., 2000). Similarly, a 50% reduction in methane yield was noted for waste activated sludge when the pH is reduced from 7 to 5 (Latif et al., 2017) and this was attributed to an alteration in the microorganisms community which favours acidogenesis microbes with a corresponding 88% decrease in methanogens. Therefore, depending on the acidity or alkalinity of the substrate during digestion process, buffer solution is usually added.

Calcium carbonate (Ca_2CO_3), hydrochloric acid (HCL), sodium bicarbonate ($NaHCO_3$) and their derivatives are the frequently used buffer solutions for the AD systems (Abdulkarim and Abdullahi, 2010)**.**

2.2.2.5 Retention Time

Retention time signifies the contact time between biomass and microbes. It is generally categorised into the Hydraulic Retention Time (HRT) and Solid Retention Time (SRT). While SRT is the average time solid components of the sludge is held in the digester, the HRT is the average time liquid content is held in the digester (Angelidaki and Sanders, 2004). A decrease in SRT reduces the rate of the reaction and vice versa (Appels et al., 2008). Accordingly, whenever solid is removed, a fraction of microbial cells is withdrawn which must be indemnified for by cell growth to thwart system failure (Ibid). Importantly, the specific methane production and digestion stability are particularly affected by the HRT. In their work, Kim et al., (2006), noted highest methane yield with HRT of 10 days while highest biogas production was obtained at 10 days HRT for a three stage digestion of food waste. Similarly, Gaby et al., (2017) observed an increased in methane production from 3600 mL/day to 7800 mL/day when the HRT was decreased, in a thermophilic digestion of food waste, from 17 days to 10 days. This could be attributed to the unavailability of biomass at prolonged HRT which reduces microbial growth rates and consequently impaired methane production.

2.2.3 Potential of anaerobic digestion in Nigeria

Nigeria has a huge potential for the anaerobic digestion systems due to the large availability of agricultural residues, animal wastes, organic fraction of municipal wastes and industrial wastes. However, most of these potentials remain untapped largely due to high initial capital costs, poor technical understanding and inadequate biogas policies and implementation strategies (Simonyan and Fasina, 2013). Various studies had been conducted on the energy potentials of AD systems in Nigeria some of which are:

A study conducted by Adeoti et al., (2001a) on the energy potential of Nigerian agricultural wastes through anaerobic digestion shows that about $3.78 \text{ X } 10^6 \text{ m}^3/$ day of biogas can be produced. A similar work by Simonyan and Fasina, (2013) also reported that 2.01 EJ of energy can be produced from agricultural wastes. Recently, Adeoti et al., (2014a) equally demonstrated that about $1.62 \times 10^9 \text{ m}^3$/annum of biogas can be generated from livestock wastes. The study also added that 683,600-ton CO_2 emission can be avoided per annum. A combination of the above wastes with the organic fraction of the municipal solid wastes had been shown to have prospect of producing 25.53 billion m^3 of biogas per year and 88.19 million m^3/ year of organic fertilizer (Ngumah et al., 2013). More so, authors observed that about 66% of domestic consumption of kerosene could be replaced with the biogas if the country’s potential is properly harnessed. In their recent work on biogas potential of domestic food wastes, Longjan and Dehouche, (2018) demonstrated that the bio-methane potential of Nigerian food wastes varies significantly from 35–460 m^3 $tonne^{-1}$. The study also shows that about 31 TWh yr^{-1} of biogas can be generated from food wastes which is enough to satisfy energy demand of 4.7×10^{-7} Nigerian households.

2.2.4 Concluding remarks on AD process

AD is a versatile approach to sustainable management and recovery of both energy and material resources from organic waste. However, detailed attention must be put on peculiarities of the biomass feedstock to determine its specific treatment requirements and matching same with conditions suitable for the optimum growth of the microbial communities. Hence, factors such as temperature, pH, HRT, and Carbon Nitrogen ratio must be properly monitored to enhance stability and effectiveness of the digestion system. More so, Nigeria has huge organic waste resources that is suitable for AD systems. However, government must provide an enabling environment for these resources to be tapped.

2.3 Overview of absorption system

An absorption cycle has the operational principle presented in Figure 2-5. Heat is supplied at the generator (desorber) where the refrigerant is vaporised and then sent to the condenser where it rejects heat to the heat sink, usually at ambient temperature, which could be air or water thereby liquefies (Araujo et al., 2017). Its pressure is then reduced which causes its expansion before being sent to the evaporator where evaporation is achieved through low temperature heat input resulting in a beneficial cooling. Different sources of hot media (liquid or gaseous) at temperature above ambient can be used to drive absorption system (Jiang et al., 2017). To increase the efficiency of the system, one or more heat exchangers (solution-solution or refrigerant-refrigerant) are usually used to enhance internal heat recovery (May et al., 2011). Commonly, heat rejection by the chiller is the same as the summation of heat input at generator and heat absorbs for production of chilled water.

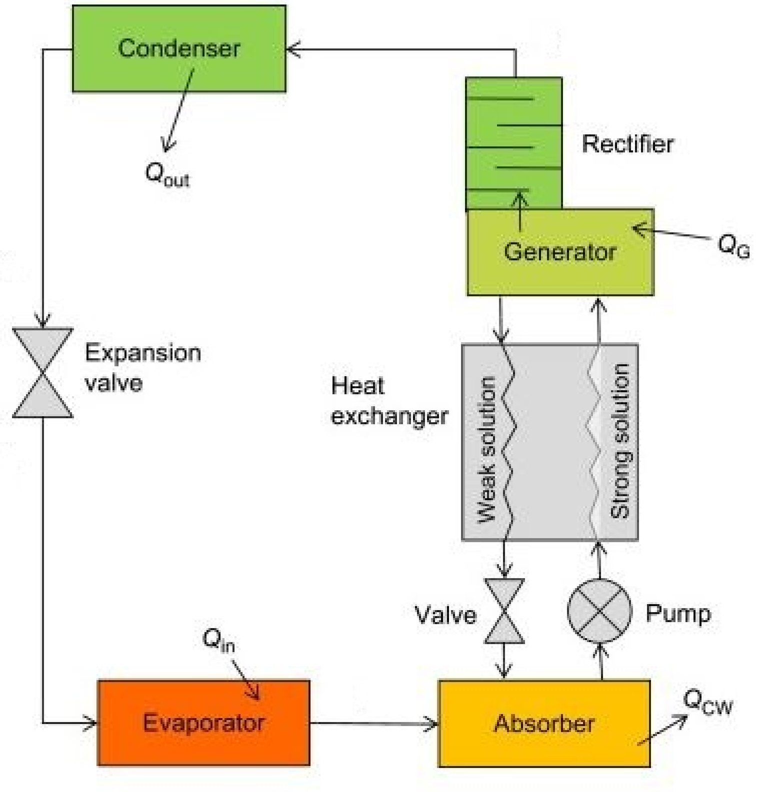


Figure 2-5: Operational principle of absorption cycle (Dimian et al., 2014)

The operational conditions of absorption cycle is as follows (Dimian et al., 2014; López-Villada et al., 2014; Srikhirin et al., 2000):

I. Low working temperature and pressure are necessary at evaporator to vaporise refrigerant which enables it to absorb heat from the chilled water.
II. It is a steady state system.
III. In absorber, the composition of sorbent solution is a function the temperature of heat sink.
IV. The pressure of generator is the same as condenser.
V. The temperature used in the generator is that needed to evaporate the refrigerant from the absorbent solution while that of absorbers is that which ensures equilibrium condition of refrigerant/ absorbent mixing.
VI. Pump is used to increase the pressure while pressure reduction is achieved using expansion valve.

The efficiency of an ARS is often presented as the Coefficient of performance (COP) defined (López-Villada et al., 2014) as in equation 2.6.

$$\text{COP} = \frac{Cooling\ obtained\ at\ evaporator}{Heat\ input\ for\ the\ generator + work\ input\ of\ the\ pump} \qquad (2.6)$$

2.3.1 Absorption refrigeration working fluids

Two working fluids are required for the absorption refrigeration system (ARS): a refrigerant and absorbent solution. Generally, the conditions required for a pair of fluids to be considered for the ARS (Herold et al., 2016; Zogg et al., 2005; Moné et al., 2001;Srikhirin et al., 2000) are:

- The pair must have high miscibility within the operational temperature range.
- Large difference in boiling points between the pair.
- Good transport properties for effective heat and mass transfer.
- Low cost, chemically stable, non-explosive, non- corrosivity, and environmental friendliness

There exist more than 40 refrigerant compounds and 200 absorbent compounds in the literature (Srikhirin et al., 2000 ; Jiang et al., 2017b) out of which NH_4-H_2O and H_2O-LiBr are the most frequently adopted (Sun et al., 2012).

Water serves as refrigerant in H_2O-LiBr absorption chiller while LiBr solution is the absorbent. In H_2O-LiBr absorption chiller, water experiences a phase change in condenser and evaporator while LiBr solution undertakes changing in concentration at absorber and generator (Yin, 2006). Water is an outstanding refrigerant due to its high latent heat. However, its freezing point is 0^0C which limits the extent of its utilization. However, H_2O-LiBr absorption system has high volatility ratio, not toxic and environmentally friendly (Srikhirin et al., 2000).

Another frequently used absorption pair is ammonia-water (NH_3-H_20) system. In such cycle, ammonia serves as refrigerant while water acts as sorbent. The freezing point of ammonia is -77^0C, making its applicable for chilling below 0^0C. However, the boiling points of the fluids are very close which serves as set back since water vapour escapes with ammonia vapour to the condenser (Somers, 2009). Water then freezes at evaporator, blocks the tubes and reduces the systems efficiency. Rectifier is frequently used in NH_3-H_2O absorption cycle to knock-out ammonia vapour and increases purity of ammonia before entering condenser. Ammonia is also considered toxic and not environmentally friendly. However, depending on its nature, food is usually stored between -18^0C to 15^0C (Kilcast and Subramaniam, 2011) but the agricultural produce of interest in this study are living tissues which, to avoid chilling injury, must be stored above 5°C. Therefore, lithium bromide absorption unit is selected due to its suitability for the aforesaid temperature ranges.

2.3.2 Thermodynamics of absorption cycle

Two commonly used approaches for the thermodynamic analysis of absorption cycles found in literature are: the summation of all thermodynamics characteristics into a simplified algebraic equation (Samanta and Basu, 2016; López-Villada et al., 2014; Seddegh and Saffari, 2015) and the use of ARS components design such as coefficients of heat transfer, area of heat exchanger, and feature of working fluids to predict and improve the performance of the ARS (Yin, 2006; Martínez et al., 2016; Manu et al., 2018).

First and second laws of thermodynamics are the principles upon which thermal efficiency of ARS are assessed (Dimian et al., 2014). The former is concerned with energy preservation while the later describes the quality of energy and materials. The numerical equations controlling the circle and its components are often offered and solved to evaluate the system's behaviour. Using such approach, Sedigh and Saffari (2011) studied a 900 kW single stage ARS and suggested that the COP of the system could be increased with increasing temperature of the generator but to an optimum generator's temperature. Besides, an increased absorber's temperature was found to have a greater effect on the COP than a similar temperature increment of the condenser. Similarly, Samanta and Basu (2016) observed that for a single stage ARS, the optimum temperature of the generator drops with increasing evaporator temperature and declining condenser temperature. Thus, identification of optimum temperature for ideal combination of condenser and evaporator was suggested.

More so, (Martínez et al., 2016) developed a TRNSYS based simulation of a 17.6 kW commercial ARS using thermal properties of the heat exchanging systems at the generator, evaporator, absorber and condenser where the overall heat transfer coefficient (UA) and inlet temperatures are the inputs. A nonconformity between the evaporator load and generator heat input was observed when there is a deviation in the evaporator temperature indicating that the unit is only designed to work within a constrained evaporator temperature. Importantly, the UA of the evaporator would need to be modified if a different heat input is to be used. Notwithstanding the differences, the developed model was said to be suitable for the performance prediction of any ARS provided that the UA of the heat exchangers are known.

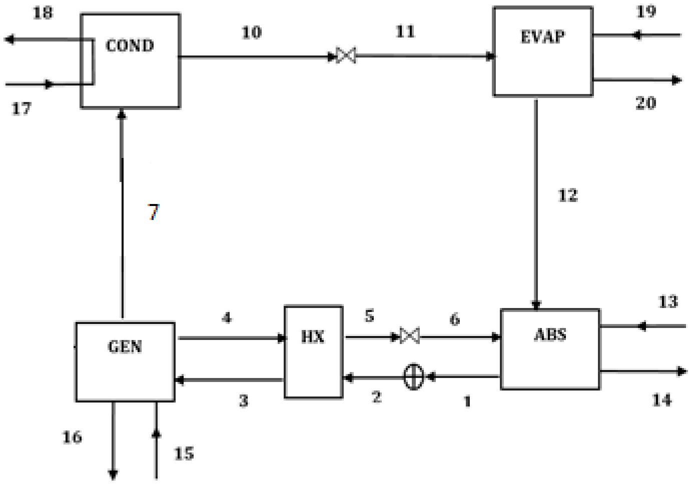


Figure 2-6: Single effect lithium bromide absorption cycle

Thermodynamically, an absorption cycle can be represented as shown in the Figure 2-6. With such graphic representation, each unit could be modelled as heat exchanger (generator [GEN]; absorber [ABS]; condenser [COND], and evaporator [EVAP] and the thermodynamic properties of both the fluids and the heat transfer units can be accessed. The circle starts from 1 where the refrigerant rich solution is pressurised. On its way to the GEN, the strong solution (SS) exchanges heat with the weak solution (WS) 4 coming from the GEN and it also get heated. Thus, improving internal heat recovery. The SS is heated in the GEN and got separated into refrigerant 7 and WS 4. The refrigerant proceeds to the condenser where it reject heat to the cooling medium, liquefied and expanded before reaching the EVAP. While in the low-pressure EVAP, it removes heat from the chilling water, vaporised and proceeded to the ABS where its absorption with the weak solution takes place. Therefore, each of the above units could be considered as thermodynamic control volume and both mass and energy balance can be executed. Thus, the material balance can be expressed in equation 2.7 while the specific mass balance e.g. for lithium bromide is shown in the equation 2.8.

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out} \qquad (2.7)$$

$$\sum_{in} \dot{m}_{in} C_{in} = \sum_{out} \dot{m}_{out} C_{out} \qquad (2.8)$$

Where ṁ is the mass flow rate (kg/hr), C is the concentration of lithium bromide while subscripts *in* and *out* symbolise inlet and outlet of the control volume. Similarly, conservation of energy within control volume can be expressed as in equation 2.9.

$$(\sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out}) + (\sum Q_{in} - \sum Q_{out}) + W = 0 \qquad (2.9)$$

Where $\dot{m}$, h, Q, and W represent mass flow rate, enthalpy, heat transfer rate and work input respectively.

2.3.3 Concluding remarks on absorption cooling process

An overview of absorption system has been presented. Details of its working principle and reasons of the choice of lithium bromide working fluid was highlighted which is due to its suitability to handle various cooling requirements of agricultural products of interest. Details of mass and energy balance of the cycle upon which both experimental and modelling of the system's behaviour, performance and improvement have been based was also presented. Therefore, Aspen Plus simulation of the cycle would be based on this approach details of which is presented in the section below.

2.4 Aspen Plus Software

Aspen Plus is a communicative and adaptable process simulation tools for conceptualised design, process enhancement, operational development and management for chemical, polymer, metallurgy, minerals and power industries (Aspen Technology Inc., 2000). It is equipped with loop analyser that is capable of handling recycling processes. It has built-in components which is the collection of common industrial processes. AP breaks down processes into unit operations which symbolises the modules. Modules are interconnected using material, work and heat streams to obtain a complete process flowsheet. Besides, individual modules in AP can be incorporated with FORTRAN or Excel environment for evaluation, modification or personalisation of a process.

More so, AP is equipped with large database of conventional pure components and phase equilibrium data for gaseous, liquid and solid organic and inorganic materials. Importantly, it is furnished with material based called nonconventional components through which materials (such as biomass) not available on the database can be added. However, the user is obliged to supply some fundamental physical, nonphysical and thermodynamic properties of such materials such as melting point, boiling points, molecular weight, density, heat of formation etc. with this, AP can estimate the remaining properties of the materials that may be required.

The shortcomings of AP are its complexity which needs substantial efforts for handling; it also does not have biological components in its database and modifications has to be done before being used by the user. Thus, this can enhance chances of error in some of these applications if not properly handled. Notwithstanding these deficiencies, AP has the following advantages over some of the existing simulation tools:

a. It has an extensive collection of built-in models for direct use such as reactors, mixers, heat exchangers, pump, compressors, etc.
b. It can be improved through various discretionary supplementary components - Dynamic, Aspen Energy Analyser, Aspen Custom Modeller, etc.
c. Can be combined with other programming languages such as FORTRAN, Excel and Matlab.
d. It is flexible such that large flowsheet can be built into subsets.
e. It is said to have the world's most widespread property database.
f. It has wide applications both in industries and academic in process design and optimisation. For instance, AP has widely been used in gasification of biomass (Keche et al., 2015; Ramzan et al., 2011;Sun, 2014), anaerobic digestion of processes (Calispa Aguilar et al., 2017; Lamidi et al., 2017a; Nguyen, 2014; Rajendran et al., 2014), absorption chilling (Bonab et al., 2015; Mansouri et al., 2015; Somers, 2009), convective drying (Janaun et al., 2016; Morey et al., 2014; François et al., 2013) and combined heat and power systems (Borello, 2012; François et al., 2013; Trendewicz and Braun, 2013).

Though, it is challenging to model a biological process like AD in AP due to non-integration of biological processes into its library database. Notwithstanding, few attempts had been made in the past to use AP in this regard.

A steady state modelling of microscale power system containing gasification and AD units was presented by Loeser and Redfern, (2010) using AP software. However, rather than modelling the complex biological processes of the AD unit, an amount of solid conversion and methane production rate was assumed. Thus, a 100-200 m^3 CH4/ ton of solid waste was considered as the major objective of the study was thermal optimisation of the integrated system. Similarly, Nguyen et al., (2014) employed AP to predict energy potential from the food waste fraction of Vietnam municipal solid wastes. The detailed biological processes were ignored, and the stoichiometric reactor of AP was used with the Buswell equation to estimate biogas generation from different scenarios. Validation of the model was conducted by comparing the model's prediction with the theoretical results from Buswell equation. However, the limitation of this approach is that Buswell equation assumes 100% degradation of feedstock and in using the equation, a conversion efficiency is always assumed. Therefore, this approach is only suitable for substrate of known degradation efficiency.

Lately, Rajendran et al., (2014) employed AP for the simulation of AD process to estimate the biogas production from different biomass under various conditions. The simulation which was based on ADM1 (Batstone et al., 2002) used RYIELD reactor of AP for the hydrolysis step while the remaining three stages: acidogenesis, acetogenesis and methanogenesis were modelled with the stoichiometric (RSTOICH) of the AP software. Details intermediate reactions and kinetics of the systems were provided. The model was validated against experimental results from other studies (Palatsi et al., 2011; Forgács et al., 2012; Budiyono et al., 2011 and Kaparaju et al., 2009). The results indicated that the model compare favourably with these empirical studies except for the anaerobic digestion of municipal solid waste which reportedly had above ±10% difference. However, the model was developed to predict biogas production bus not composition and therefore, other components such as free fatty acids, alkalinity and effect of nitrogen concentration were overlooked. A similar approach was used by Calispa Aguilar et al., (2017) to calculate energy generation from co-digestion of food waste (FW) and primary sludge (PS) under different scenarios with varying operating conditions. A mixing ratio of 1:2 of FW to PS was considered suitable for both mesophilic and thermophilic conditions. At this mixing ratio the model was in agreement with experimental studies with about 5% disparity. Notwithstanding, the model is not good at predicting the quality of biogas since it was not designed for such purpose. Besides, the aforesaid reactions were equally ignored.

Meanwhile, a comprehensive modelling of food waste AD process with AP was developed by Nguyen, (2014) using ADM1 which was adapted to include ammonia inhibition of acetoclastic methanogenesis and a “metabolic switch” that allows availability of trace elements to be modelled. The model, when compared to the experimental data of sugar beet anaerobic digestion, was able to estimate both biogas quality and quantity at OLR not exceeding 4 $gVSL^{-1}$.However, the use of the model requires comprehensive data about the feedstocks including trace elements from both feedstock and digestates. Hence, notwithstanding the limitations of (Calispa Aguilar et al., 2017; Rajendran et al., 2014) and (Peris, 2011) in predicting biogas quality, they are very good at estimating biogas production under various operational conditions and require minimum data about the feedstocks They are also thought to be good models for the AD of heterogeneous organic wastes such as agricultural residues which is the focus of this study. Therefore, these models would be adapted for the current study.

2.5 Postharvest loss of agricultural produce in Nigeria

In Nigeria, approximately 45% of food produce is been wasted during post-harvest handling: harvesting, packaging, transportation, marketing and consumption (Abubakar and Agbo-Paul, 2013) and could be as high as 95% depending on the produce and season (Adepoju, 2014). This is even more pronounced at the earlier stage of agricultural value chain unlike developed countries where food waste is predominant at retailing and consumption stages (Stuart, 2009). The loss tends to be higher for vegetables such as tomatoes, pepper, green leaves, oranges etc. especially during harvesting seasons when production is usually more than supply. This is because, crop production is predominantly rain-fed, and crops tend to mature and ripe at the same time. Thus, loss occurs due to unavailability of storage facilities or agro-allied companies that can make use of the excess crops. For instance, Nigeria is the second largest producer of tomato in Africa with about 1.5 million metric tons produced in 2011, 60% of which get wasted. Therefore, about 300,000 tons was imported to meet up with 1.2 million metric tons demanded and thereby making the country the highest importer of tomato in the world (Hassan et al., 2013).

Food waste in most Nigerian states are left to decay in the environment, drawing flies, cockroaches, rodents and other pathogens of public health concerns and many outbreaks of diseases in the past, in different parts of the country, had been attributed to wastes (ibid). These wastes are also an eyesore, they create foul odour due to slow decay. Since 1999 Nigerian federal government policies have pushed for increased production of food by concentrating on enhancing agricultural production via soft loans, provision of agricultural tools and equipment to the farmers. However, this has led to bigger generation of food waste as provisions are not made for suitable processing and storage of agricultural produce. This is largely due to the energy crisis on which postharvest food storage and processing largely depends. Presented in the Table 2-3 are some selected studies on PHL in Nigeria.

Table 2-3: Selected studies on postharvest loss of agricultural produce in Nigeria.

Study	Agricultural produce	Outcome
Adepoju, (2014)	Tomato	• About 95.5% PH loss experienced.

		• Losses significantly impact the per-capita income. • PH processing & storage recommended.
Mada et al., (2014)	maize, cowpea and groundnut	• Adoption of post-harvest machines increases economic impact by 40%. • Post-harvest loss (PHL) ranges between 15-20%
AGRA, (2014)	Grains, legumes and tuber crops	• PHL differs across agro-ecological zones • PHL varies from 9-35% for grains, 16-29% for legumes and 16-22% for tubers crops.
Suleiman and Rugumamu, (2017)	Sorghum	• PHL fluctuates between 8.43% and 13.12% depending on PH storage system used. • Threshed sorghum tends to have more storage loss than un-threshed.
Adegbola et al., (2011)	Citrus, plantain, pawpaw,	• PHL varies from 5-95% for citrus, 35-100% for banana and 40-100% for pawpaw while pineapple records around 70% loss.
Olayemi et al., (2012)	Fish, yam, cassava, maize, plantain and vegetables	• PHL varies with 35%, 37.33%, 27.67%, 20.33% 27% and 33% for fish, yam, cassava, maize, plantain and vegetables respectively.
FAO, (2015)	Plantain and banana	• PHL accounts for 60%.

		• Training and value addition undertook.
Babalola et al., (2008)	Pineapple	• 74.9% PHL was observed. • Results in 24% economic loss to the farmers.

2.6. Renewable energy sources, potential, and its regulations in Nigeria

Renewable energy is continuously restoring energy sources by nature. It could be directly obtained from sun (thermal, photo-chemical, and photo-electric), indirectly from sun (wind, hydropower, and photosynthetic energy reserved in biomass) or other natural environmental movement or mechanisms (geothermal and tidal energy) (Ellabban et al., 2014). It does not encompass energy from fossil fuel and its derivatives. These energy sources are turned into useful energy forms: electricity, heating and transport fuels by renewable energy technologies and it has been observed that above 3000 times (Gilliam, 2015) the current global energy demand can be produced from the renewable energy sources. The overview of the renewable energy sources is illustrated in the **Error! Reference source not found.** while Nigeria's potential is shown in Table 2.4. However, of interest to this study are agricultural residues from crop and animal sources details of which are discussed in Chapter 3.

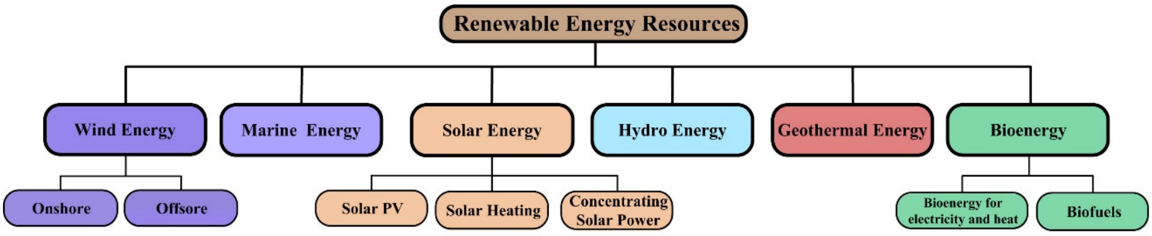


Figure 2-7: Overview of renewable energy sources (Ellabban et al., 2014)

Table 2-4: The renewable energy potential of Nigeria.

Energy Type	Capacity	Source(s)
Large Scale hydropower	10,000MW	(Akinbami, 2001)

Small scale hydropower	734MW	(NERC, 2005)
Fuelwood	13,071,464 hectares	(Ngumah et al., 2013)
Animal waste	61 Million tons/year	(Shaaban and Petinrin, 2014)
Crop residue	83 million tons/year	(Akuru and Okoro, 2010; NERC, 2005)
Solar Radiation	1850x 10^3GWh/year (3.5-7.0 kWh/m^2/day	(Oyedepo, 2012)
Wind	150,000 TJ/year	(Oyedepo, 2012; NERC, 2005)

Overview of the policies and regulations related to the renewable energy in Nigeria is presented below

Regulation and management of electricity was purely under the control of federal government through Energy Commission of Nigeria. Energy generation, transmission and distribution were centralised and under the control of government's owned National Electricity Power Authority (NEPA). The supply system prioritised electrification of major cities, states capitals, and the headquarters of all the 774 local governments. The motivation factor was more political than social and economic considerations. However, in 2003, the National Electricity Policy was produced (Aigbovo and Ogboka, 2016). The policy highlighted the multifaceted nature of energy including financing, pricing, human capital development, and regulation. The policy recognised need for private sector involvement in energy sector development, need to decentralise the existing structure and tapping into the renewable energy potential of the country. The policy became law in 2005 through the establishment of the Electricity Power Sector Reform Act (EPSRA, 2005). With the policy, the operational status of NEPA was shifted from public corporation to private company (Ohiare, 2014). Hence, NEPA was renamed the Power Holding Company of Nigeria (PHCN). However, with the full implementation of EPSRA, the energy infrastructure was to be private driven. PHCN was therefore split into business units: Transmission Company of Nigeria (1) (TCN), Distribution Companies (11) (DisCos) and Generation Companies (6) and while government still retains TCN, both GenCos and DisCos are purely private driven. The Nigerian Electricity Liability Management Company was also set up to deal with the stuck assets and liabilities of the outdated NEPA. The act also provides for the establishment of the Nigerian

Bulk electricity Trading Company which is an electricity bulk-trader that purchases electricity from the GenCos through power purchase agreements and sell same to the DisCos through vesting contracts. To supervise the industry and guarantee global best practices, two regulatory agencies: the Nigerian Electricity Regulatory Commission (NERC) and the Rural Electrification Agency (REA) were formed (Rural Electrification Agency, 2015). NERC licenses and regulates energy generation and distribution systems above 1MW electricity generation and below 100 kW distributed electricity. Generation and distribution units outside aforementioned categories are controlled by REA while units less than 100 kW are not licensed but encouraged. The current work falls under the regulation of the REA. Hence, details of its policies and approaches are briefly highlighted.

The REA currently works with the Rural Electrification Policy Paper (Rural Electrification Agency, 2015) which is aimed at increasing access to electricity; enhance sustainable economic; social advancement and reduces rural-urban migration by raising living standards in rural areas through promotion of environmentally friendly alternatives to fossil fuels and fuelwood. REA also manages Rural Electrification Fund (REF) which is a government grants disbursed for rural energy systems. However, in line with the government's Renewable Energy Master Plan (Energy Commission of Nigeria, 2012) which is aimed at increasing the role of renewable energy (10% by 2025) in attaining sustainable development. Thus, a project must have a minimum of 30% renewable energy before qualifying for the REF (REA, 2017a).

To achieve 60% rural electrification by 2025, the federal government through REA aims at electrifying 10 million rural households which is to serve both domestic and non-domestic rural energy demand (REA, 2015). The required capacity is around 6000 MW which is more than the current capacity of the whole country. Meanwhile, at the moment, grid connected residential and commercial consumers hardly have electricity availability above 40 hours per week (Nigeria Bureau of Statistics, 2012);Ohiare, 2014) and this has necessitated both diesel and gasoline powered self-generated electricity within the country which presently cost between USD0.45 to 0.75/ kWh. These, self-generated systems are not only expensive but also cause both noise and environmental pollutions. Noise pollution have, in many instances, resulted in frequent clashes and social unrests within neighbourhoods. Therefore, to attract public participation in rural electrification, REA is adopting a cost reflective tariff model which peg the internal rate of return to 15% (REA, 2017b) and a tariff is agreed upon between the developers and rural communities.

2.7 Food drying

2.7.1 Drying and drying kinetics

Drying is the oldest method of food preservation. The essence of drying is to remove moisture from food which is mostly water. In this case the water activity of the food is lowered, typically less than 0.6, to a level where microbial growth and reaction rate is slowed (Das et al., 2001). The process is typically accompanied by vaporizing the water that is enclosed in the product. Thus, the latent heat of vaporization must be provided (Earle, 2004). Therefore, the two guiding principles in drying are:

- Heat transfer to supply the needed latent heat of vaporization.
- Movement of water or water vapour through the food material and its subsequent separation from the food.

Drying is mostly done through air drying, vacuum drying or freeze drying (Lewicki, 2006). In either of the method, drying is achieved by taking advantage of different states of water and vapour pressure. While air drying is done at atmospheric pressure, vacuum drying is achieved at lower pressure and freeze-drying takes advantage of water vapour sublimation.

There exist different types of dryers which are classified based on the methods upon which heat and mass transfer is accomplished (Vagenas and Marinos-Kouris, 1991). Accordingly, mode of operation, heat input, operational pressure, drying medium, temperature and residence time are modes on which classification is often based. More so, the mode of heat transfer could be by convection, conduction, radiation and any other means (Ibid). Therefore, most drying processes are either convective (supplying of heat by hot air) or conductive (transmission of heat from hot walls, pipes or surfaces). Radiation (e.g. infra-red), dielectric heating (radiofrequency and microwaves) or combinations may also be used (Mujumdar, 2007).

Drying kinetics is frequently used to describe the microscopic and macroscopic mechanisms of mass, heat and momentum transfer during drying. It is greatly affected by factors such as the thermodynamic conditions, types of dryer and the physiognomies of the materials being dried (Colak and Hepbasli, 2007; Sturm et al., 2014). Thus, drying kinetics can be used in the choice of the appropriate dryer and operating conditions for agricultural produce since it accounts for the removal of moisture and the influence of other variables. The removal of moisture in food with respect to time is illustrated in the Figure 2-8 which is generated by plotting moisture loss against drying time.

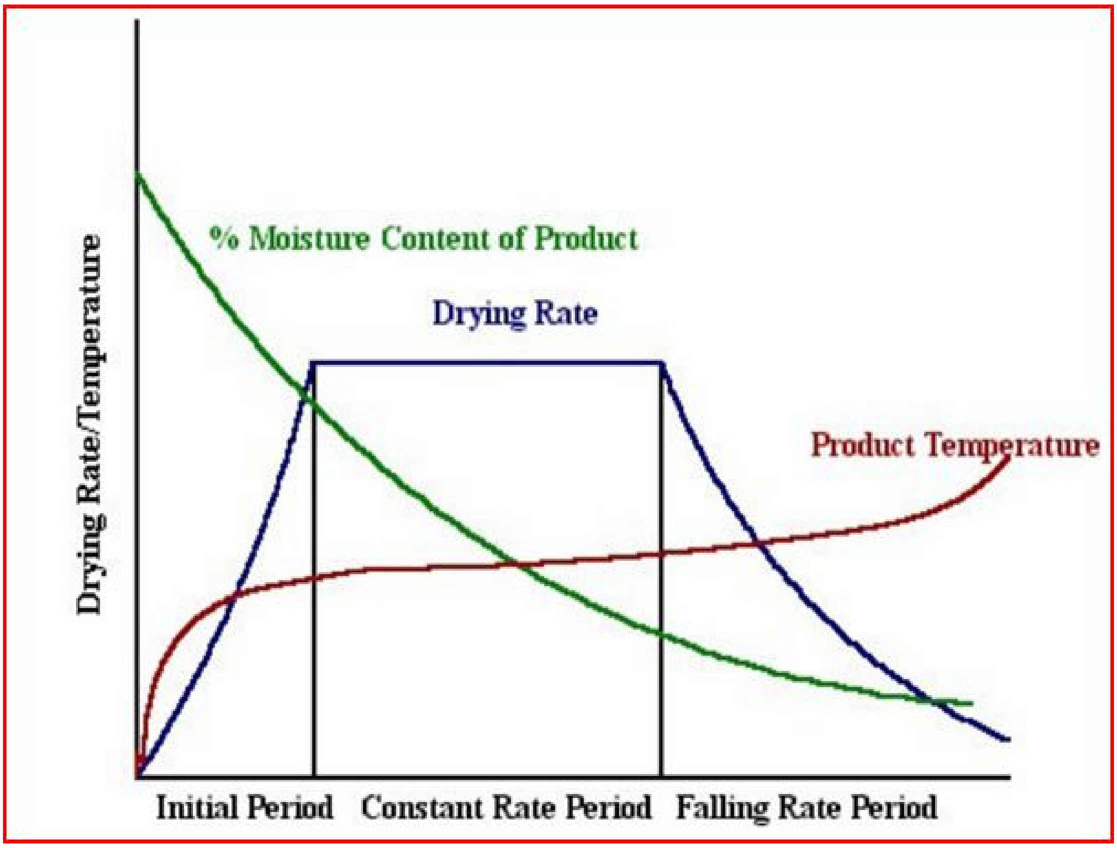


Figure 2-8: Food Drying Curve (Yang and Siebenmorgen, 2003)

At the beginning of drying (settling down period), the food sample comes in thermal equilibrium with the drying chamber after which the external moisture in the food begins to be removed (constant drying rate). Drying at this stage is mostly influenced by the drying conditions: air temperature, velocity and relative humidity. This continuous until the Critical Moisture content is reached after which Falling rate period begins. Rather than drying conditions, drying is diffusion dependent and food particle size and matrix plays significant roles at this stage (Heldman, 2003). At this stage water moves from the region with higher water content to the region with lower water content and this phenomenon is influence by the second law of thermodynamics. Drying at the falling rate period is usually accompanied with products shrinkage, deformation and other noticeable quality loss.

2.7.2 Factors affecting drying

Drying is often accomplished by transfer of heat from drying medium to the product being dried. As noted earlier, the drying rates of products during the constant drying period is a function of heat transfer while drying during the falling drying the rate is mass-transfer dependent. Drying of agricultural products is known to be influenced by many factors such as relative humidity (Colak and Hepbasli, 2007; Inazu et al., 2002), drying temperature (Patel and Kar, 2012; Premi et al., 2010; Simal et al., 2005), air velocity (Ghasemkhani et al., 2016; Punlek et al., 2009; Sturm et al., 2014), type and sizes (Nabnean et al., 2016; Sharma et al., 2009) of the product being dried etc.

Relative humidity which can be defined as the amount of water vapor in the air, expressed as a percentage of the maximum quantity that the air could keep at the particular temperature is one of the major factors that influences rate of drying (Celma and Cuadros, 2009; Faith et al., 2005). The lower the relative humidity, the higher the ability of the drying air to absorb moisture from the product. This is because dynamic equilibrium is established between the moisture in the solids and the vapour in the drying air and this phenomenon affects rate of drying (Kemp, 2007a). However, this dynamism is often influenced by drying temperature. Hence, in designing of convective dryers, humidity and temperature are the most frequently controlled parameters. During dryer design, one of the tools that is often used is the temperature- humidity psychrometric charts. Given the drying condition (product quantity, moisture content, ambient temperature and relative humidity) and expected output (final moisture and targeted exit relative humidity of the dryer exhaust) psychrometric charts can be used for the determination of the required air flow and size of the dryer (Kemp, 2007a). Other factors often been controlled for adequate drying are air velocity and product size.

2.7.3 Simulation tools for drying

Improvement of drying efficiency is often accomplished by optimisation drying operating parameters or reconfiguration of the dryers. However, studying these experimentally is both costly and time consuming. Thus, modelling and simulation with software are otherwise being adopted to model, simulate and optimise dryer and drying conditions. The result of the simulation is then designed and fabricated. Use of computer programming software in food drying is classified into (Kemp, 2007b):

a) Calculation programs such as one used for numerical modelling e.g. SPSS, Microsoft Excel, spreadsheet.
b) Process simulator.
c) Expert systems and related decision tools.
d) Information delivery or online data base.
e) Auxiliary calculations such as psychometric and humidity chart.

The choice of these tools is based on the extent of information required by the user and the intended use. After user might have provided the required information, sensitivity analysis, sizing, equipment designs can be carried out with the model (Lamidi et al., 2019a). Details of some selected studies on application of software for drying is presented in Table 2-5.

Table 2-5: Selected publication on applications of numerical modelling tools in drying (Lamidi et al., 2019a)

Modelling approach/ Software used	**Agro-produce**	**Study criterial/ research findings**	**References**
Matlab to solve Crank-Nicholson drying model	Cocoa beans	• The moisture content reduced from 50% to 7% within 7 days.	(Yeboah, 2012)
Drying kinetics modelling with Matlab	Potato	• Drying optimisation carried out and Page model allegedly perfectly predicts potato drying	(Olawale and Omole, 2012)
Simprosys	Lignite	• Increased power generation by 1.3% and a reduced cost of energy delivery	(Xu et al., 2015)
Combustion drying modelling with Simprosys	-	• The moisture carrying property of air and combustion gas is pressure dependent.	(Mujumdar and Zhen-Xiang, 2014)
CFD	Potato	• Drying time reduced with ohmic heating as moisture diffusion in the product is enhanced leading to a	(Moraveji et al., 2010)

		simultaneous heat and mass transfer.	
CFD	Apple	• Large-eddy simulation was found to be more accurate than the Reynolds-averaged Navier-Stokes turbulence model but at high computational cost. • Combination of the former with low Renolds number modelling gives a better accuracy	(Defraeye et al., 2013)
TRANSYS and CFX	-	Finned PV air collector with V shaped desiccant bed are able to give a uniformed air distribution	(Punlek et al., 2009)
GAMBIT and FLUENT	Greenhouse simulation	Inhomogeneity of air profile within the dryer detected.	(Lokeswaran and Eswaramoorthy, 2013)
FLUENT	-	Diagonal air flow gives a better distribution of air flow	(Amjad et al., 2015)
FLUENT	Kenaf Core	• Different configurations tested and one with better air profile selected • Good agreement between simulation and experimental results	(Misha et al., 2013)

Fluent	Apple	• Vapour diffusion was found to be more dominant than freeze drying process at temperature below 0ºC. • Diffusional resistance of porous tissue was also revealed by CFD.	(Lia et al., 2007)
Fluent 12	Horticultural products	• Reynolds-averaged Navier–Stokes (RANS) was joined with the shear stress transport k-ω model for the microscale modelling of horticultural products. • The model was found to have a good result over a wide range of Reynolds number (10–3 × 10^4).	(Defraeye et al., 2012)
Fluent	-	• The roof of greenhouse dryer was found to be the coolest part of the dryer which also serve as the heat sink. • The CFD model reportedly in good agreement with experimental data and able to predict the condensation, temperature and humidity change within	(Piscia et al., 2012)

		the dryer and gives a good design considerations for the humidity control especially in unheated greenhouse dryer	

2.7.4 Application of Aspen Plus for drying

Aspen Plus is one of the tools that have been widely used for simulation of drying units. Aspen Dryer and DRYSCOPE are packages within Aspen Plus which are specifically designed for drying. The drying model is based on the drying kinetics, drying curve, heat transfer coefficient and the number of heat transfer units. Aspen Plus presumes that biomass molecular weight is 1g/mol. Consequently, water should have a coefficient of 0,0555084 (Lakshmanan and Reimers, 2013). Depending on the user’s requirement, co-current, counter current and crosscurrent drying can be designed for the convective dryer, bed and fluidised bed dryers.

The user is also expected to define the biomass composition such as the fixed carbon, volatile matter, ash and ultimate composition. More so, resident time and particle size of the biomass must be specified (Aspen Technology Inc., 2015). However, one of the limitations of using Aspen Plus for drying simulation is that it assumes constant rate drying kinetics (Kemp et al., 2004) whereas drying kinetics is drying time dependent and not fixed during drying processes. Notwithstanding this limitation Aspen Plus has been widely adopted in modelling and designing of drying units for the drying of solids and liquid materials.

An industrial drying-air heating system with a rectangular cross flow shell and tube heat exchanger was investigated for the drying of powder milk by Ribeiro and Andrade, (2004). Saturated steam and hot water were investigated as heating fluid. To do this, different algorithms were developed for each of the fluids and implemented in Aspen Plus. The calculated air outlet temperatures predicted by Aspen Plus were then compared with experimental data from existing industrial milk dryer. A 6.7% and 4.3% difference were observed between experimental data and value predicted by the Aspen Plus for the saturated steam and hot water respectively. More so, (Almeida-Trasviña et al., 2015) studied optimisation of vacuum drying for Apple and Pomace. Both apple and Pomace were modelled with their respective percentage compositions while ENTHGEN and DNSTYGEN of Aspen

Plus were employed in defining the enthalpy and density of the fruits since they are non-conventional materials. The result indicates that, similar to what has been experimentally reported for other vacuum drying of fruits, the final moisture content of the product is more influenced by drying temperature while pressure and drying time have less influence.

Similarly, gasification is one of the predominantly method for recovery of energy from biomass. The process is often accompanied with initial drying of biomass and Aspen Plus has widely been used for the designing and optimisation of the gasification process. As part of an biomass integrated gasification combined cycle systems of a corn ethanol plant which involves drying of corn stover and distillers wet grains, Morey et al., (2014) studied two drying systems: steam tube and superheated steam dryers using Aspen Plus. Essence of the study is to maximise generation of electricity from the plant. The result indicates that the units with steam tube dryers deliver 20–25 MW with the average thermal efficiency of 71.5 while plants with superheated steam dryers produce 20–22 MW of power to the grid with system thermal efficiencies averaged 54.5%.

2.7.5 Overview of sustainable drying of agricultural produce

Quest for sustainability, food security and need to decouple food prices from the fluctuating prices of finite fossil fuels are the drivers to sustainable processing and storage of agricultural products.

Therefore, a sustainable drying is the drying of agricultural produce with little or no fossil fuel input. It sought the use of alternative fuels or energy source in carrying out agricultural produce drying thereby reduce impact of food drying on environment. Hence, the approach to sustainable food drying either involve (Kemp, 2012):

- Improving the efficiency of the dryer which may be achieved through insulation, heat recovery or altering the systems operating constraints.
- Improving or substituting the system’s energy supply by using Combine Heat and Power (CHP), biomass derived fuels or renewable energy sources.

Thus, based on the above, drying can be sustainably carried out by solar system, biomass units, geothermal system, waste/recovered heat or combination of two or more systems called hybrid drying. The approach to sustainable drying is presented in the Figure 2-9. Importantly, details of these approaches had been summarised into an article and published. More so, this study uses both combined power and heating as well as biogas burner to power a convective dryer for sustainable drying of agricultural products.

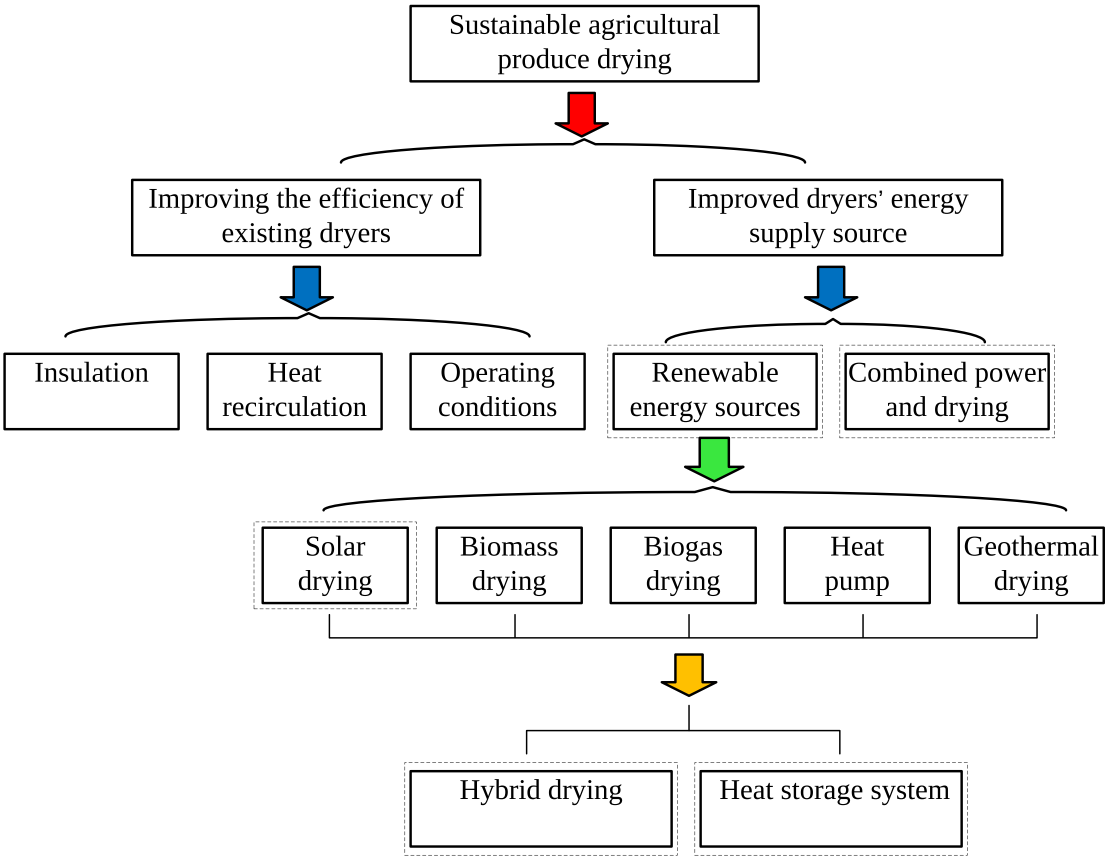


Figure 2-9: Sustainable drying approaches (Lamidi et al., 2019a).

2.8 Summary

Viability of CHP systems strongly depend on the onsite or near-site availability of both electrical and thermal energy demand. The overall system efficiency is particularly influenced by systems' configuration and ability to utilise low grade heat. In addition to the aforementioned, price volatility of fossil fuel and availability of financial incentives such as grants, tax relief and Feed in Tariffs influences the economic feasibility of CHP units.

Biogas powered combined heat and power system is being proposed as a solution to the above-mentioned challenges of heavy PHL and energy poverty within the rural areas of the Sub-Saharan African region. While most of the energy sources presented in the Figure 2.9 would have addressed issues of sustainable drying, a system that is able to: a) provide electricity; 2) heat for drying; 3) sustainable heat for cooling of agricultural products; 4) sustainable energy for cooking as well as provide organic manure for soil enrichment and closing the loop of nutrient cycle is thought to be the best option. Various studies have reported using biomass CHP either for an on-farm drying of agricultural products (Bennett et al., 2007; Samadi et al., 2014; Samadi et al., 2013) or production of electricity, domestic hot water and other rural settings requirements (Jimenez et al., 2012; Khan et al., 2014; Loeser and Redfern, 2010). Bennett et al., (2007) studied a biomass CHP where corn Stover was used as CHP fuel. The produced heat was used to dry shelled grain while generated electricity was used to power fans, augers, and control components. Two sizes of dryers were studied: a) (8.9 Mg h-1), and (73 Mg h-1) suitable for small and medium farms respectively. Using $25 $(Mg)^{-1}$ as fuel price and 20 years life span, the lifetime cost savings and breakeven points of $63,523 and 14.3 years and $1,804,482 and 7.5 years were estimated for small and medium units respectively.

Loeser and Redfern, (2010) studied a conceptualised 50 kWe micro-scale biomass CHP for rural community. The model used AD for energy recovery from wet biomass while gasification was utilised for solid waste. The produced biogas and producer gas were stored in a tank at 5 bars for suitability in micro-turbine operations and subsequently used to power the turbine. Heat is recovered from the turbine exhaust and used to power gasifier. The whole system was modelled with Aspen Plus software and the results indicated an electricity generation efficiency of 28% while the combined efficiency was 86%. The produced electricity was said to be enough to power about 200 rural households. However, the economic viability of the system is strongly influenced by discount rate, the plant capital costs and the revenues base unit price.

Similarly, Jimenez et al., (2012) presented their proposed work of a 86 kWe gasifier biomass fuelled CHP for a 60 Brazilian rural households. The recovered heat from the gasification unit was used for biomass drying while another one is recovered from the generator for domestic water heating. A part of the produced producer gas was also used for domestic cooking. The results suggested that the configuration can supply 86 kWe of electricity and 65 kW_{Th} estimated for domestic, commercial and community usage with LCOE of US$0.0618/ kWh against US$0.115/kWh from the grid.

More so, Khan et al., (2014) studied a biogas fuelled poly-generation system for rural Bangladesh households. A fraction of the biogas is used for cooking while the rest is used to fuel a micro-turbine. Heat is recovered from the turbine exhaust and used to power an air gap membrane distillation unit for water purification where arsenic constitutes the major water impurity. The results indicated the levelised cost of (0.015 USD/kWh), (0.042-0.048

USD/kWh) and (0.003 USD/L) for cooking gas, electricity and drinking water respectively. More so, subject to the operational circumstances, a payback period of 2.6-4 years was reported.

The above studies clearly demonstrated applications of CHP to numerous challenges of rural settlements. However, these studies were found to follow either of these approaches:

- Focus on the agricultural energy demand without considering the domestic energy needs of the farmers.
- Evaluate and address the domestic energy need of the farmers without considering farming energy requirements.

Therefore, these provide rational for this study and would be shown to be pertinent to the Sub-Saharan African region that is not only currently at the bottom of energy ladder but also faces challenges of food insecurity as well as desert encroachments induced by high pace of deforestation. Hence, to the best of this researcher’s knowledge, no study has reported energy generation systems that synchronised electricity generation with cooling and drying of agricultural products as well as provide cooking gas and organic manure particularly from Sub-Saharan Africa region. Thus, this study details:

1. A systematic study on the farmers’ energy demands (domestic and postharvest processing related); estimation of renewable bio-wastes resources available locally; potential of using such wastes to generate biogas.

2. A holistic solution for agri-products processing using the renewable bio-wastes; supply electricity to the villagers; provide biogas for cooking.

Chapter 3 : Evaluation of farming and domestic energy demand of rural households

3.0 Introduction

As noted in the section 2.1, an important requirement of CHP system is the availability of local demand for heat and electricity. This is because both the technical and economic feasibility of such systems are strongly influenced by the on-site and near-site thermal and electrical energy demands particularly the system’s ability to use low grade heat. Therefore, details of the approach used for energy demand estimation and the results are discussed in this chapter.

3.1 Methodology

Two approaches are used for the estimation of energy demand: 1) The field visit; 2) structured questionnaire survey. Two villages within the same district were selected for the survey. The two villages were purely agrarian communities in Ibarapa Central Local Government area of Oyo state Nigeria and about 142 Km north of Lagos and 122.9 kilometre west of Ibadan. One of the villages (Idere) has been connected to the national grid for more than a decade though the electricity availability hardly exceeds 40 hours per week. The second village –Jagun is never connected to the national grid, has around 500 households living in about 200 houses and huts. The essence of the survey in Idere is to use its electricity consumption pattern as yardstick in the projection of the future electricity demand of Jagun village. The two villages belong to the same district having similar cultural and agricultural activities. This is because these two factors greatly influence use of energy across Nigeria especially preference for freshly cooked foods and influence of geo-ecological zones on agricultural activities.

3.1.1 Questionnaire survey

The farmers are predominantly illiterates or semi illiterate and do not speak English language which is the language in which the questionnaire is written. However, a nearby village is currently used as the research village for an ongoing cassava research project-CAVA II which is a Bill Gates foundation sponsored project and being implemented by the International Institute of Tropical Agriculture, Ibadan and the Federal University of Agriculture Abeokuta. So, eight research students from CAVA II project who are native language speakers helped in the oral administration of the questionnaires. The volunteers were first briefed on the objectives of the survey and the brief was followed with training during which questions on the survey were taken one after the other. Mock administration of the questionnaire in the local language were conducted during the training session.

Using simple random sampling, one hundred farmers are selected from Jagun village. The criteria used are 1) Adults farmers; 2) permanent settler on the village and 3) Self-employed farmers. This is because, based on the tradition within the area, a young adult may still be working with or for his parents. Hence, the independence age varies between 18 and 25 years depending on the circumstances. For instance, a young adult male farmer who is the only son of the family is more likely to become independent and settle down earlier than his counterpart with aged parents.

Idere is about ten times more populous than Jagun village. So, to get reasonable representative sample, a two-stage stratified random sampling is adopted. The hierarchal traditional administrative structure within the area is shown in the Figure 3-1. The highest authority within a town is the king (Miles, 1993) who usually has many villages and compounds under him. Villages could be some miles away from the town, the town itself is divided into clusters of blood related extended families called Compounds (Ezenwaji, 2002; Fajonyomi, 1997) which is governed by Bales while the head of each extended families called “Olori ebi” also report to Bale. There are about 500 households in Jagun village and considering time and resources it was not possible to involve all the households in the survey. Thus, 20% of the total households were involved in the survey. This is considered representative enough as one out of every five households within the village have chance of being selected. Idere comprises of about sixty compounds half of which is classified as big while the remaining half is regarded as small compounds. Therefore, these compounds are taken as enumeration areas from which three and two respondents are randomly selected from each of the big and small compounds respectively. Hence, 150 questionnaires are administered in Idere while 100 questionnaires are administered at Jagun village.

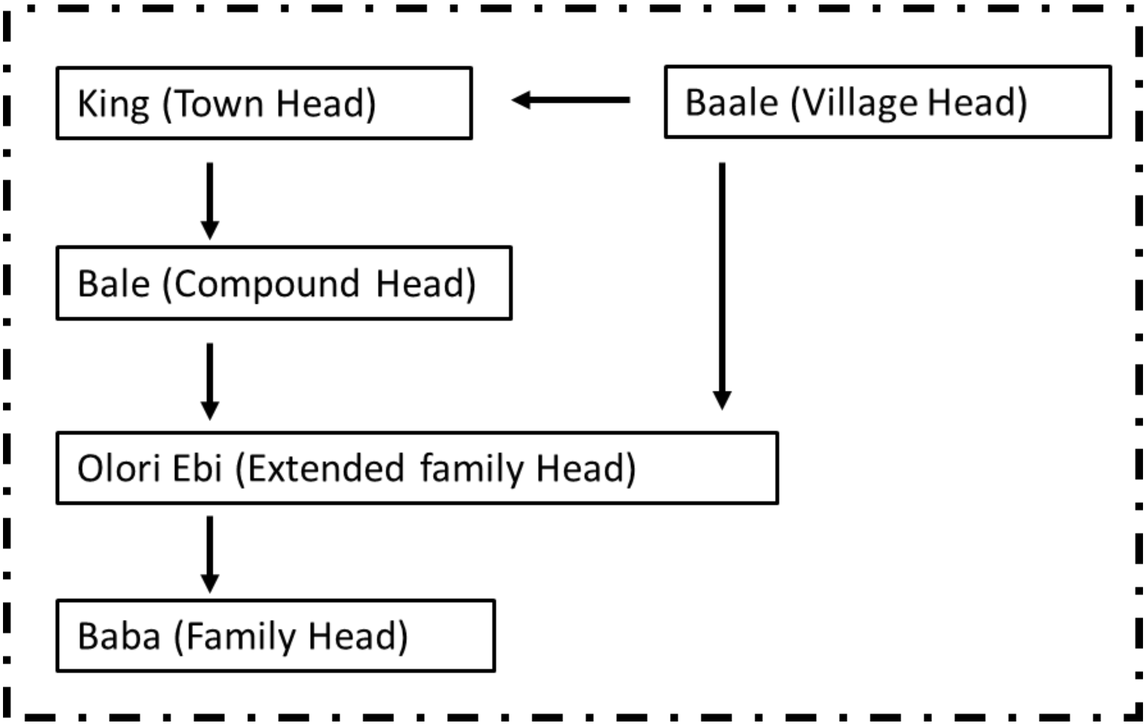


Figure 3-1: Hierarchy of local administration of the study area

3.1.2 Stakeholders meeting

The survey was carried out between July and September 2017. The village has a local authority primary school which serves the village and other neighbouring villages within the zone. The head-teacher is well respected within the area. So, the head-teacher was first approached and briefed who subsequently organised meeting with the village head. The essence of the meeting is to inform them on the objectives of the research and the impact such findings can have on the wellbeing/agricultural activities. At the request of the village head, another meeting involving family heads was held during which September 22-24 was agreed for the administration of face-to-face questionnaire survey. Presented in the Figure 3-2 is the image at the village square.

Figure 3-2: Cross-section of villagers with the head-teacher and village head.

3.1.3 The design of the questionnaire for the survey

The survey is face-to-face administered questionnaire. The presentation, language and structure of the questionnaire makes it easy to understand and requires less than 10 minutes to complete. To elicit the required information from the farmers, the questionnaire is divided into three sections: sections A, B C. Questions related to the demographic characteristics of farmers such as age, gender, education and marital status were asked. The essence of this is to assess the effect of these factors on farming knowledge, energy use and possibly farmers' tendency to adopt new technologies. Section B of the questionnaire is dedicated to energy usage. Culturally, while some farmers' households are living in single house, most farmers do live in shared apartment where more than one household could be living in a single building. This trend usually affects the usage and choice of energy. Thus, questions related to house type, energy source for lighting and cooking, quantity and usage durations of basic households' materials such as radio, television, mobile phone, refrigeration, fan and lamps were asked. The last part of the survey-section C seeks information on farm activities related energy demand. Information sought in this section are the farm size, crops planted, numbers of times being planted, and the share of the farming land being currently occupied by different crops. During administration of the questionnaire, it was observed that farmers are more comfortable remembering the bundle(s) of fuelwood used per week. Hence, weighing balance (Model: Hana, China) was used to determine the average weight of the fuelwood bundles. Sample of the questionnaire is presented in the Appendix 1.

3.2 Results and discussion

This section is divided into four sub-sections: the demographic status of the respondent; farming activities, domestic energy usage and overall energy estimation.

3.2.1 Demographic status of the farmers

3.2.1.1 Farmers gender

The results (Figure 3-3) shows that, within the study area, 82% are male while 18% are female. The percentage of female farmers is smaller than 35.7% by the Nigeria Bureau of Statistics (Nigeria Bureau of Statistics, 2010) reported for the state. However, this survey was carried out with adult farmers while NBC data includes farmers from 5 years and above.

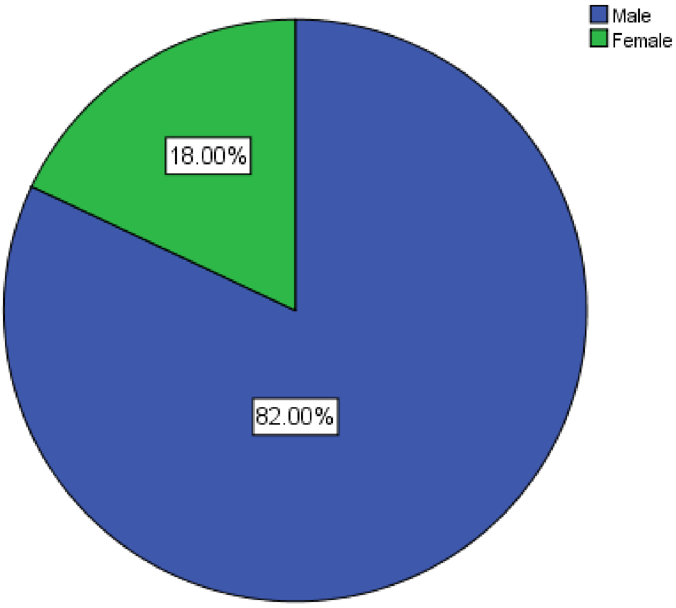


Figure 3-3: Farmers' gender

3.2.1.2 Farmers' age

The study shows that the farming population is relatively young (Figure 3-4) as age 16-55 accounts for 82% of the farmers. However, within this age block, younger farmers age 16-35 years accounts for 28% while 36-55 years has 54%. This is expected as post primary school age in Nigeria is between 16-35 years of age and government is continuously encouraging school enrolment.

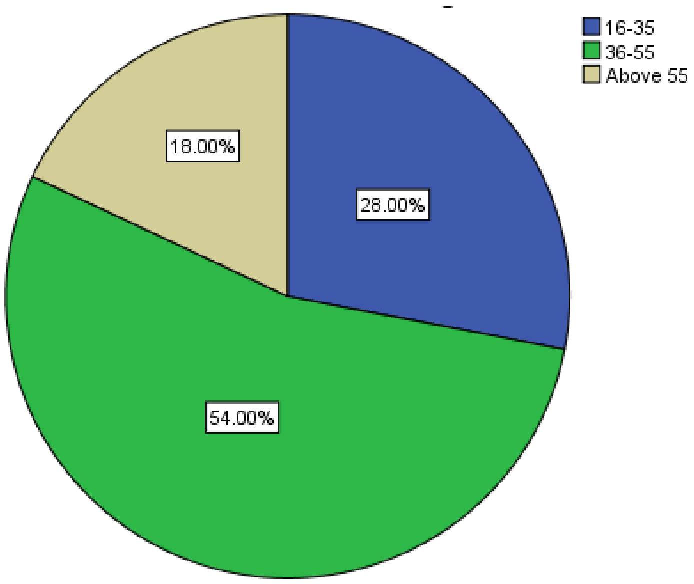


Figure 3-4: Farmers' age

3.2.1.3: Marital Status

The result (

Figure 3-5) indicates that 72 percent of the respondents are married; 14% are not married while separated, widow and divorced represents 8%; 2% and 4% respectively. However the married status is above the 64.16% of the Nigerian national average for the rural area (Nigeria Bureau of Statistics, 2010).

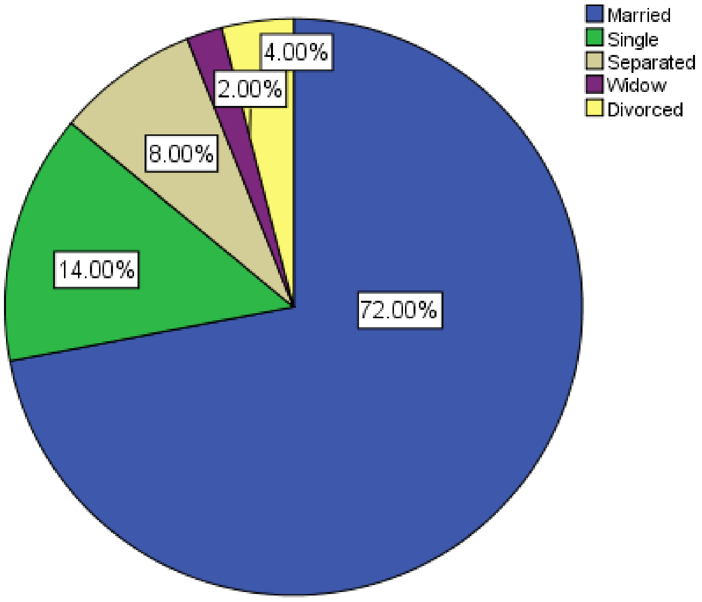


Figure 3-5: Marital status of the farmers

3.2.1.4 Educational status

The educational status of the farmers is predominantly primary and secondary schools (72%) while about 24% never have any formal education and 4% have post-secondary education (Figure 3-6). The secondary school status accounts for 34% which is bigger than 28.3% (Ibid) reported for the national rural area. However, the post-secondary school is less than 6.6% of the national average for the rural area.

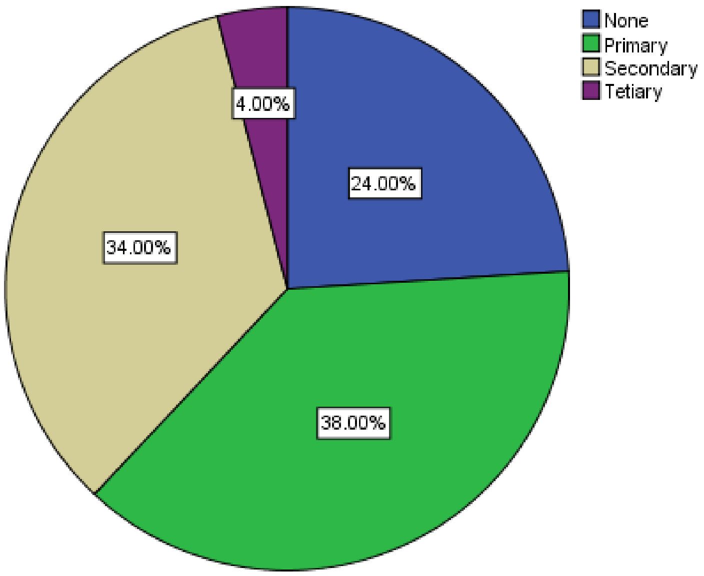


Figure 3-6: Educational status of the farmers

3.2.1.5 Housing type

An analysis of the housing type also indicates that 60% of the farmers in the study area live-in single-family house while 40% live in shared building. This is lower than 51.2% national value figure. However, the buildings (Figure 3-7) are either rectangular mud building with rust corrugated iron roofing sheets or thatch roofing made from grass and polythene bags. More so, 2 rooms apartment is the predominantly used building type

Figure 3-8.

Figure 3-7: Cross-section of farmers' and housing type.

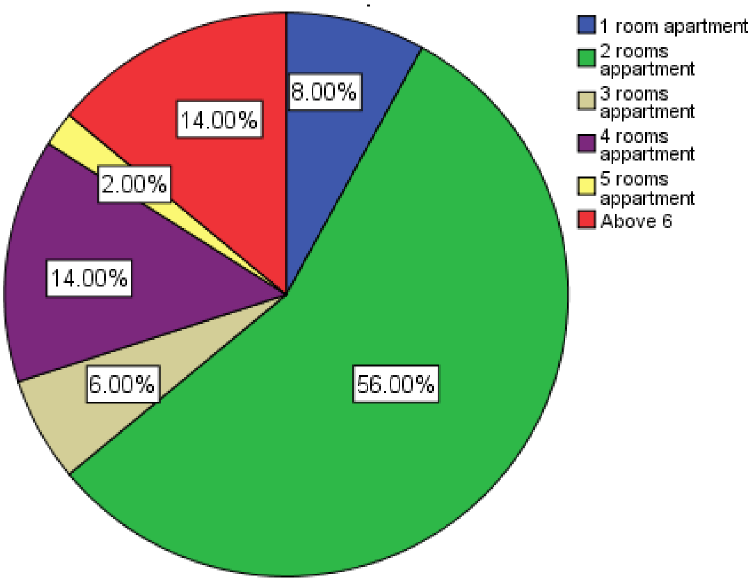


Figure 3-8: Rooms per farmers' households.

3.2.2 Farming activities

3.2.2.1 Farm size

The survey indicates that the highest farm size (Figure 3-9) within the area is 2-3 hectares (44%) which is follow by 4-5 hectares (36%) while less than 1 ha and above 6 respectively accounts for 2% and 9% of the farm sizes. The mean farm size from the study is 2.7ha. Meanwhile, the average farm sizes reported in the literature varies across regions with average 4.2 ha per household in the North (Soneye, 2014) while about 1.6 ha/household has been reported for the south (Eze et al., 2011;Awotide et al., 2016). Therefore, the mean farm size of 2.7 ha/household is adopted in this study.

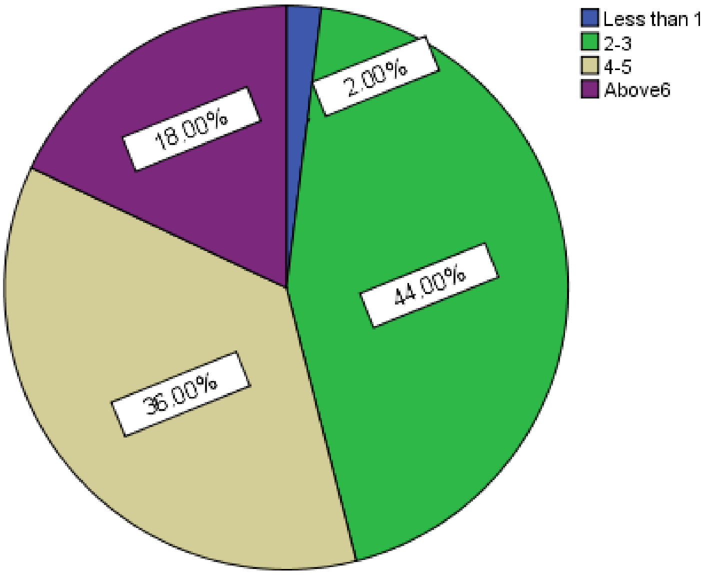


Figure 3-9: Farm size.

3.2.2.2 Crop Planting

Cassava, maize, sorghum, yam, cowpea, groundnut, millet, rice, cocoyam and oil palm tree are the most cultivated crops in Nigeria, the prevalence of which varies across different geo-ecological zones (National Bureau of Statistics, 2012). Hence, farmers were asked on the type of crops cultivated, and the response is presented in the (Figure 3-10). From the figure, cassava, maize, tomato and cashew are the most planted crops in the study area with 100, 92, 90, and 54 respondents respectively currently cultivating the crops. This indicates that all the farmers (100%) cultivate cassava at the moment while 92%, 90%, and 54% of the farmers could be said to presently plant maize, tomato and cashew respectively.

Besides, farmers were asked of the proportion of their land currently under cultivation of the aforementioned crops (Figure 3-11). The responses were used to evaluate the mean land in acres under cropping of each of the crops. For instance, the proportion of land being used for cassava varies from 1 to 7 acres depending on the farmer's farm size but the mean size from the responses is 3.9 acres/farmer. Similarly, the mean land sizes for maize, tomato and cashew are 2.66; 1.90 and 1.20 acres respectively.

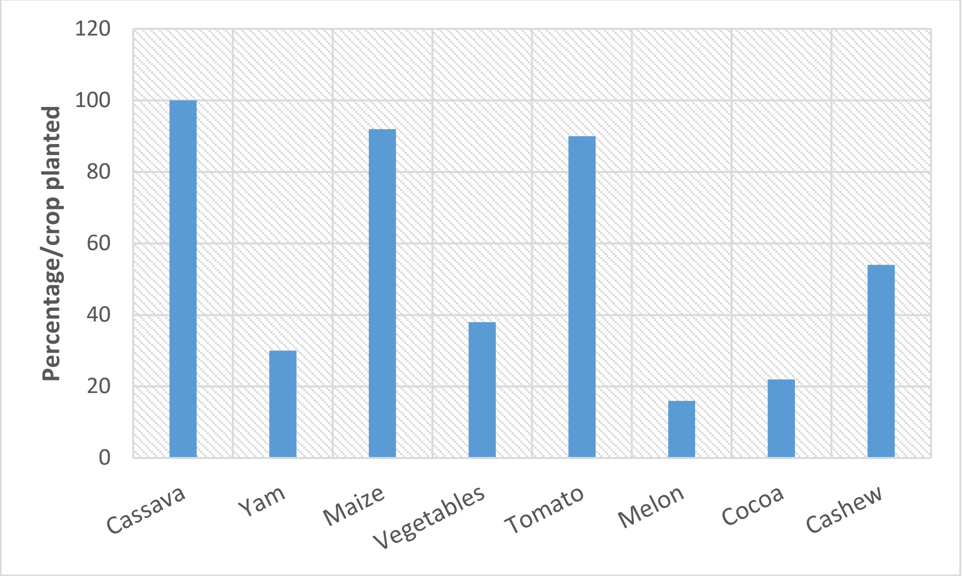


Figure 3-10: Prevalence of crop planting

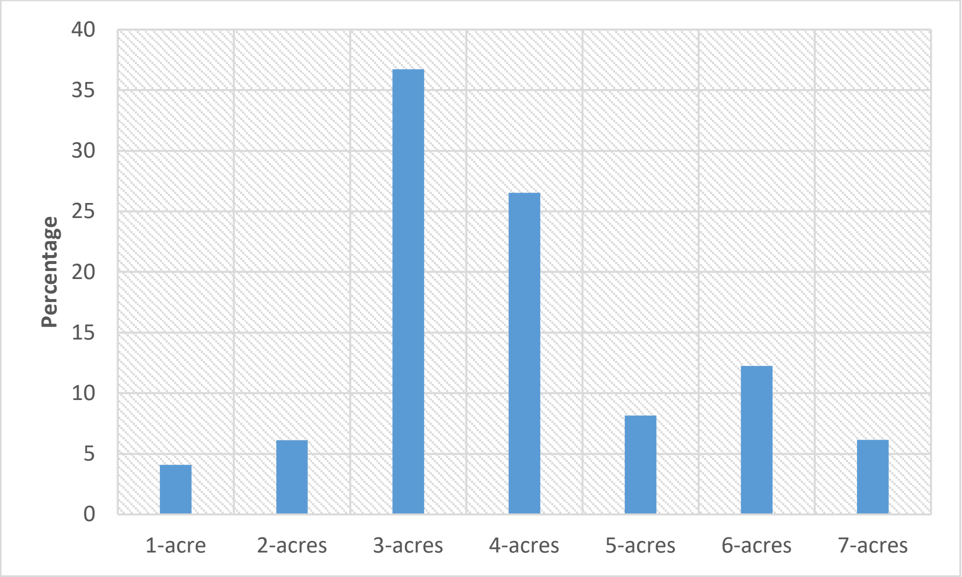


Figure 3-11: Proportion of land under cultivation of cassava

3.2.2.3 Cultivation times per year

The nature of crops which could be biannual, biennial or perennial influences the number(s) of times planting, and harvesting is done per annum. This subsequently determines the number of residues available per crop per annum. Therefore, farmers were asked the numbers of times each of the above crops are planted per year and the response per each of the crops is presented in the Figure 3-12. From the Figure, tomato and maize are planted twice in a year while cassava and cashew are planted once.

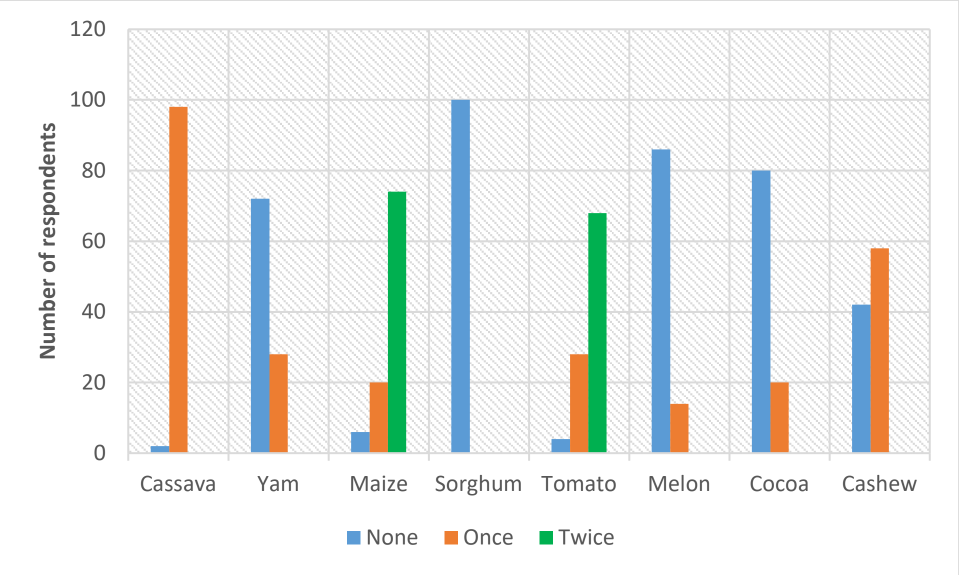


Figure 3-12: Number times planting is done per year

3.2.3 Domestic Energy Usage

3.2.3.1 Source of lighting energy

The source of lighting within the study area is heterogeneous and farmers report using more than one sources; the choice of which is motivated by factors such as cheapness, availability, conveniences, literacy level, the financial status and age of the farmers (Olatinwo and Adewumi, 2012). Hence, 100% of the farmers reported using kerosene lamp while 78%, 72%, 66% and 4% reportedly use touch light (disposable dry cell battery), rechargeable lamp, mobile phone and generator respectively. The responses are shown in the Figure 3-13. The observed predominance of kerosene usage for lighting is similar to the 85% reported by Adkins et al., (2012) for 300 rural households across the SSA region. However, the figure is far above the 68.5% reported by the national office of statistics (Nigeria Bureau of Statistics, (2010). One of the farmers with a 960W Tiger (China) generator uses it for commercial purpose as he charges #50 (£0.11) and #70 (£0.15) for charging of mobile phone and rechargeable lamps correspondingly.

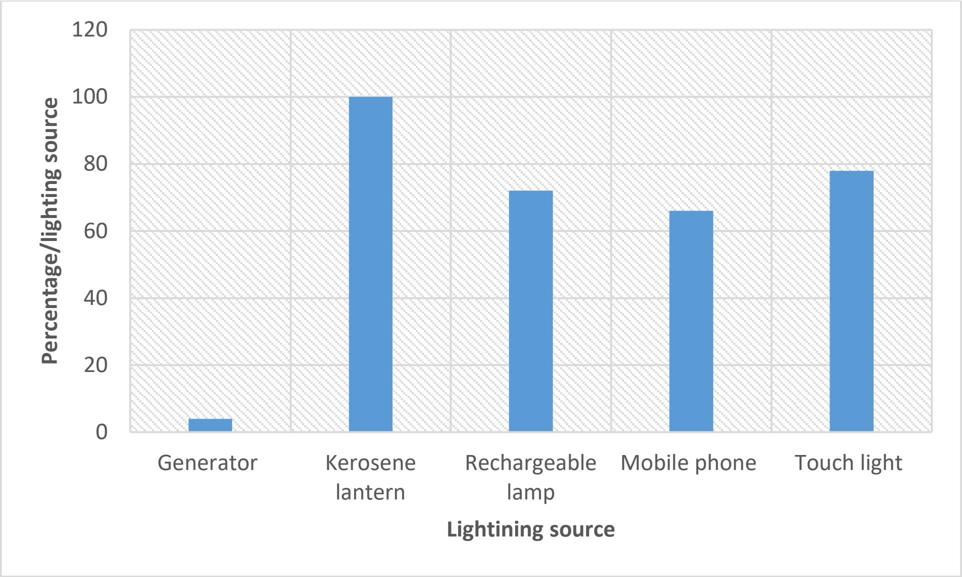


Figure 3-13: Sources of lighting.

3.2.3.2 Source of cooking energy

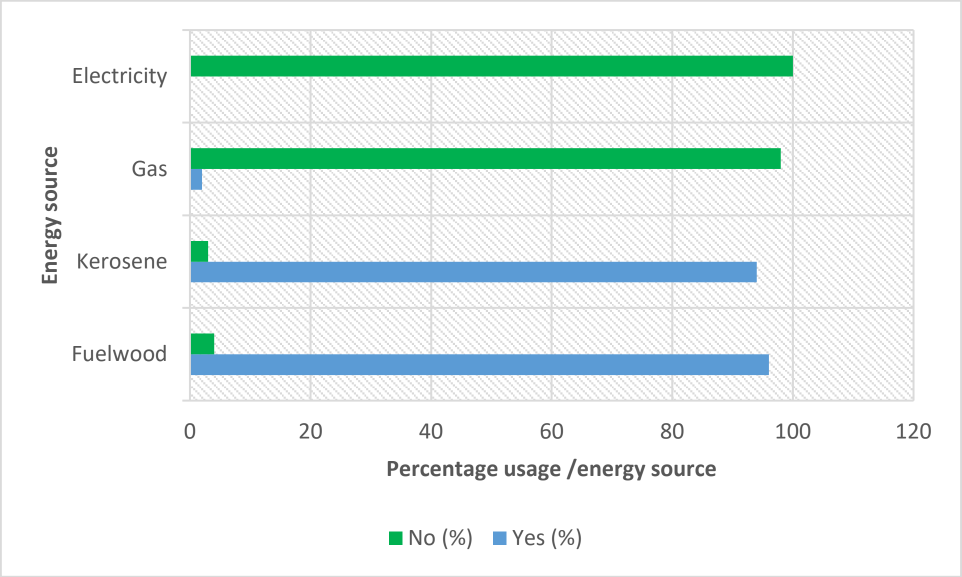


Figure 3-14: Source of household's cooking energy

Similarly, more than one energy sources is being used for cooking by the farmers with 96% of respondents using fuelwood (wood, charcoal, crop and animal residue) while 94% reportedly uses kerosene for cooking (Figure 3-14). Propane gas is the least used (2%) while none of the respondent uses electricity. The trend follows the report by Adkins et al and NBS except for the use of cooking gas which increases from 0.8 reported by the NBS to 2%. This may be attributed to the current government policies which is pushing for the domestic use of cooking gas

3.2.3.2.1 Quantity of fuelwood usage

The approach used here was to ask respondent on the numbers of fuelwood bundle (s) used per week. The weight of the bundle was found to vary greatly and mostly influence by factors such as the age of the fetcher and distance from the village. The bundles were randomly selected and weighted using weighing balance (Model: Hana, China). The weight was found to vary between 22.5 kg to 50.5 kg with 36.5 kg as the average. The percentage of households with the corresponding numbers of fuelwood used for cooking per week is presented in the Figure 3-15. From the analysis, the mean value of the bundles consumed per household per week is 1.9. Therefore, the weekly fuelwood used is 69.35 kg per household. On per capital bases this value falls within 1.2 kg to 4.5 kg per day reported for Nigeria and other African countries' rural communities (Adkins et al., 2012; Ibrahim and Ukwenya, 2012).

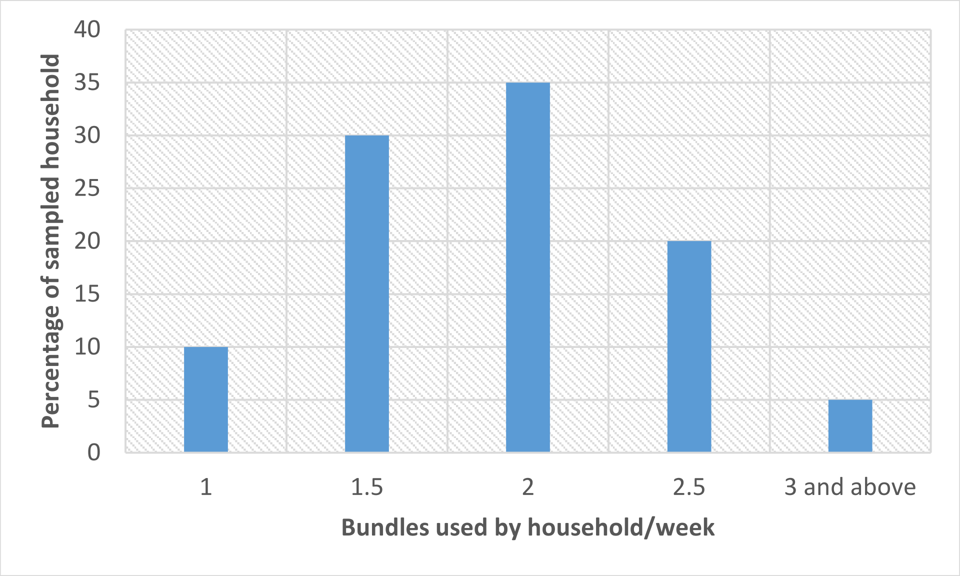


Figure 3-15: Bundles of fuelwood used by household per week

3.2.3.2.2 Quantity of kerosene usage

According to the respondents, kerosene is mainly used for lighting while some fractions are used to start fire. However, more quantity is used for cooking especially during raining seasons when fuelwood would be wet and becomes difficult to ignite. Besides, forests are bushy during this period and always challenging to go for wood gathering. Hence, more kerosene is used during raining seasons than dry seasons. According to the respondents, kerosene is usually purchased from big villages or towns in 1-gallon plastic bottles. So, the respondents were asked frequency of monthly purchase and the report is presented in the

Figure 3-16. The mean monthly purchase is 1.42 gallon which gives a 0.215 $Lday^{-1}household^{-1}$ of kerosene consumption. This value is in the same range with the data reported by Oyekale et al., (2012) but slightly more than the value reported by (Ibrahim and Ukwenya, 2012) for a rural village in the southern part of Nigeria.

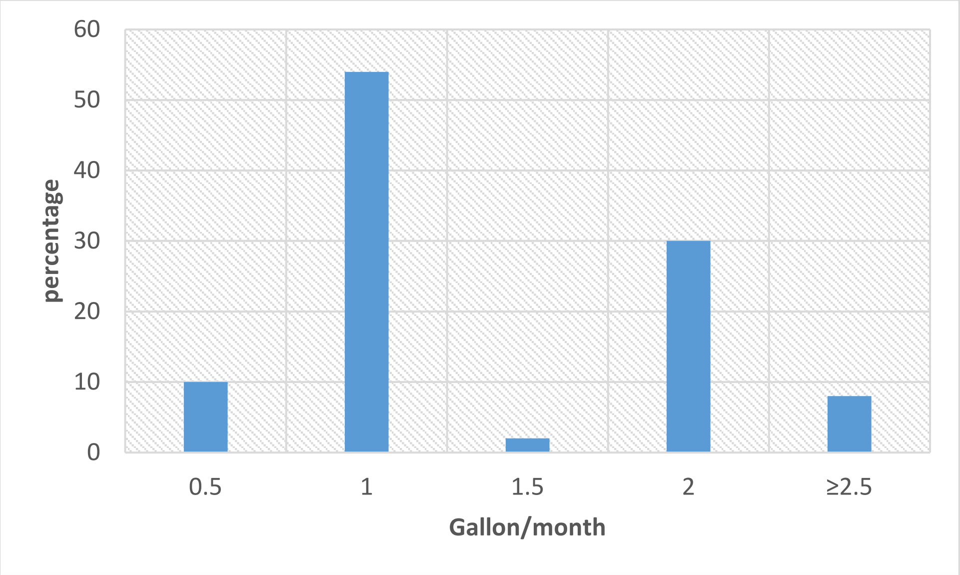


Figure 3-16: Monthly kerosene consumption.

3.2.3.3 Mobile phone ownership

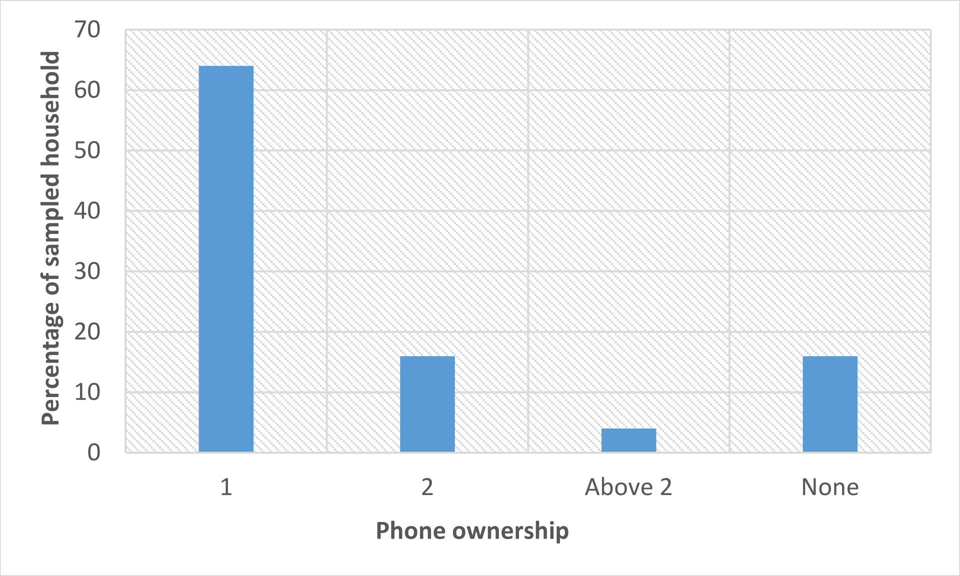


Figure 3-17: Mobile phone ownership by sampled households

The result of ownership of mobile phone is detailed in the Figure 3-17. About 84% of the farmers have mobile phone with one phone ownership account for 64% while 16% and 4%

account for two phones and more than two phones respectively. However, this value is less than the 94% (Adepetun, 2016) national mobile phone penetration.

3.2.3.4 Radio ownership

Respondents' ownership of radio is presented in the Figure 3-18. It is observed that 80% of the farmers have one radio while 16% do not have. However, ownership of cassette radio is regarded as luxury and 4% of the respondents have this type of radios in addition to the common transistor radios that is usually powered with disposable dry cell batteries.

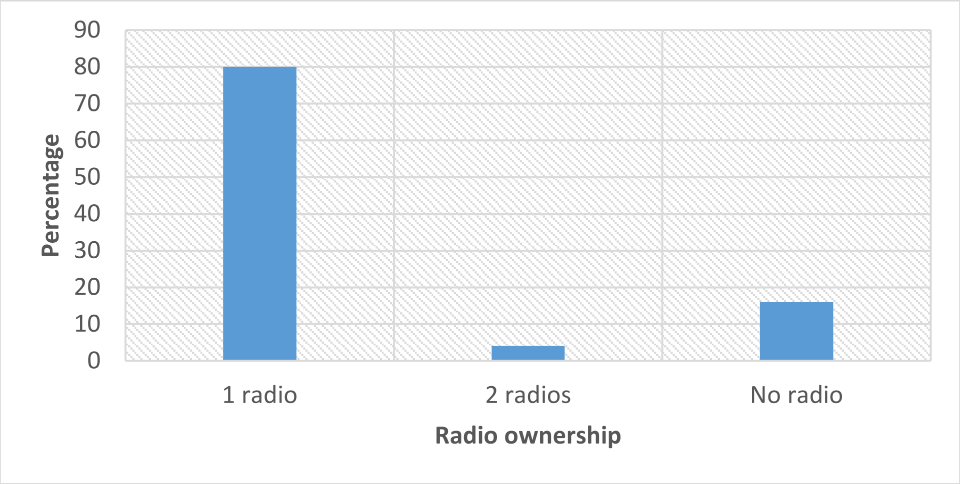


Figure 3-18: Radio ownership

3.2.3.5 Television ownership

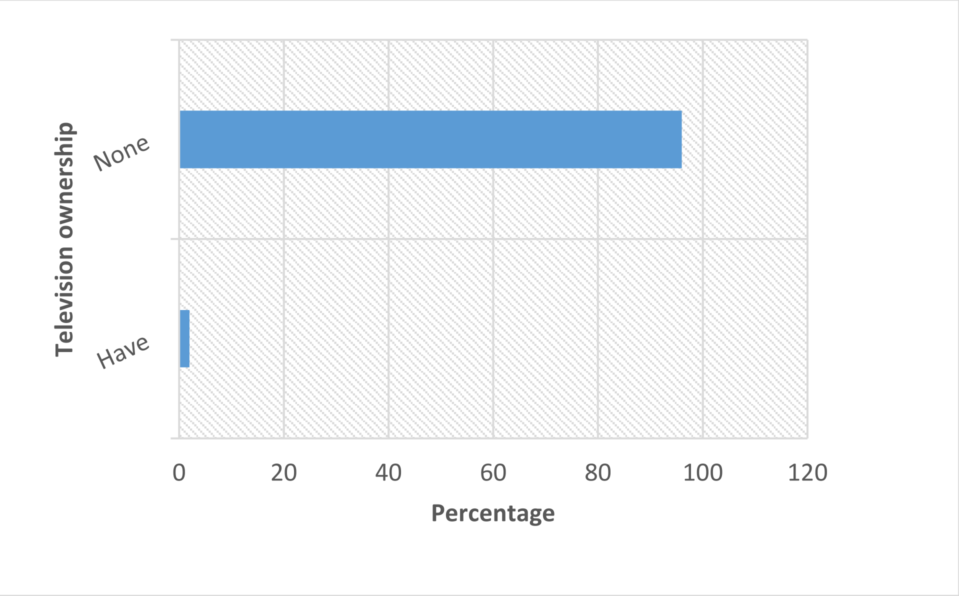


Figure 3-19: Ownership of television

About 98% of the respondents do not have television while only 2 percent currently do. It was observed (Figure 3-19) that most of those televisions are not working. The television is either broken down or the generator set is not currently working.

3.2.3.6 Ownership of disposable battery powered lamp

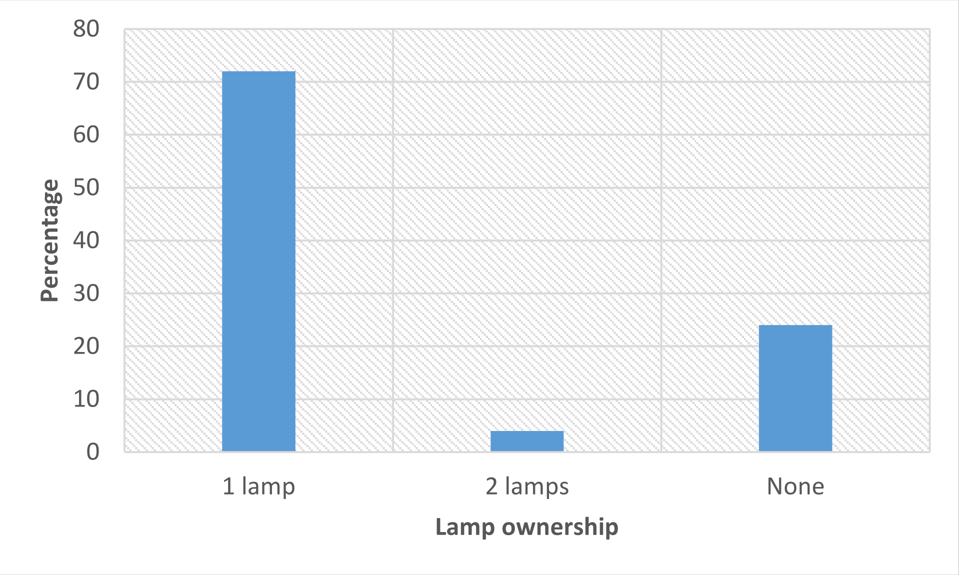


Figure 3-20: Ownership of lamp

Similar to the trend above, the ownership of the disposable dry cell battery powered lamp is presented in the Figure 3-20. About 24 % of the farmers do not have battery lamp while

76% have. Of the haves, 72% have one while only 2 % possess more than one lamps. Ownership of more than one lamps is observed within polygamous households.

3.2.4 Energy Usage of Grid Connected farmers

3.2.4.1 Demographic features and farm sizes

The demographic status of the grid connected farmers is observed to be similar to that of non-grid connected farmers. However, the average farm size is around 2.45 ha/household as against 2.7 ha/household observed for the non-grid connected farmers. This may be associated with the population density of Idere. Besides, most farmers in Idere are found to have motorcycle locally called Okada which they sometimes used for intra and inter-village commercial transport services and this might have affected the farming activities.

3.2.4.2 Source of domestic energy for lighting

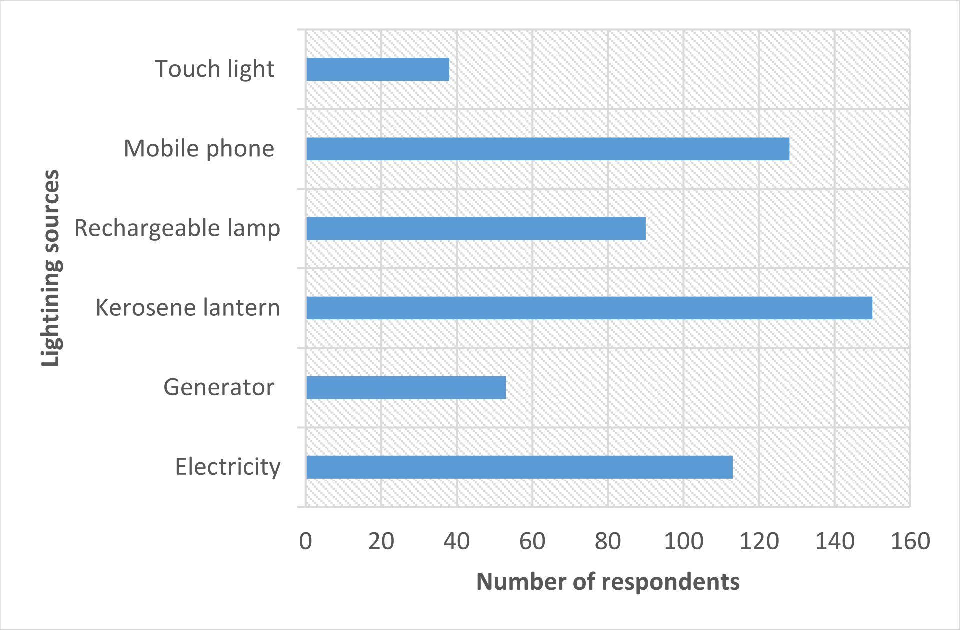


Figure 3-21: Domestic lighting energy sources of the grid connected farmers

The sources of lighting for the grid-connected farmers is shown in the Figure 3-21. All respondents (100%) use Kerosene for lighting. This is not surprising because electricity supply is very erratic (Ohimain, 2013;Adeoti et al., 2014b). However, 25% of the respondents are either never connected or disconnected from the grid due to their inability to pay for the electricity used. Rechargeable lamps also form substantial part of the lighting devices. Farmers find this easier to recharge either from the neighbours who have generator set or commercial charging centres.

3.2.4.3 Source of domestic energy for cooking

Kerosene is reportedly used for cooking by all respondents (100%) as indicated in the Figure 3.22. Only 8 respondents representing 5% reported ever used electric stove and cooking gas for cooking respectively. However, while 68 respondents use fuelwood; 113 (75%) reported using charcoal which is produced from pyrolysis of fuelwood. This they attributed to convenience since, due to the population density, they may need to travel farther into the bush for fuelwood gathering. Weekly consumption of these energy sources by the grid-connected villagers is shown in the Table 3.1.

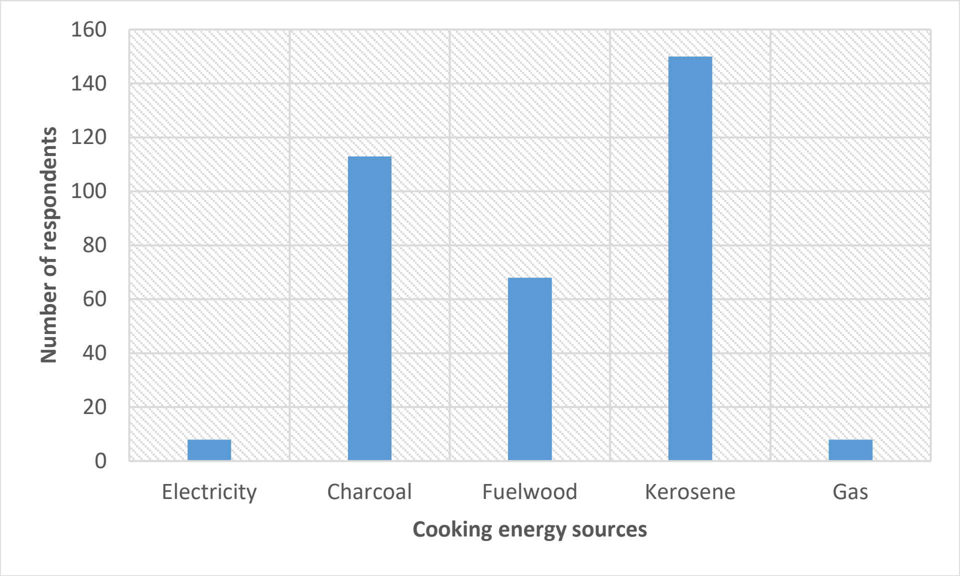


Figure 3-22: Domestic cooking energy sources of the grid connected farmers

Table 3-1: Weekly cooking energy sources consumption

Energy source	Unit	Quantity used
Kerosene	L	4.1
Charcoal	kg	11.4
Fuelwood	kg	48.6

3.2.4.4 Ownership of household devices

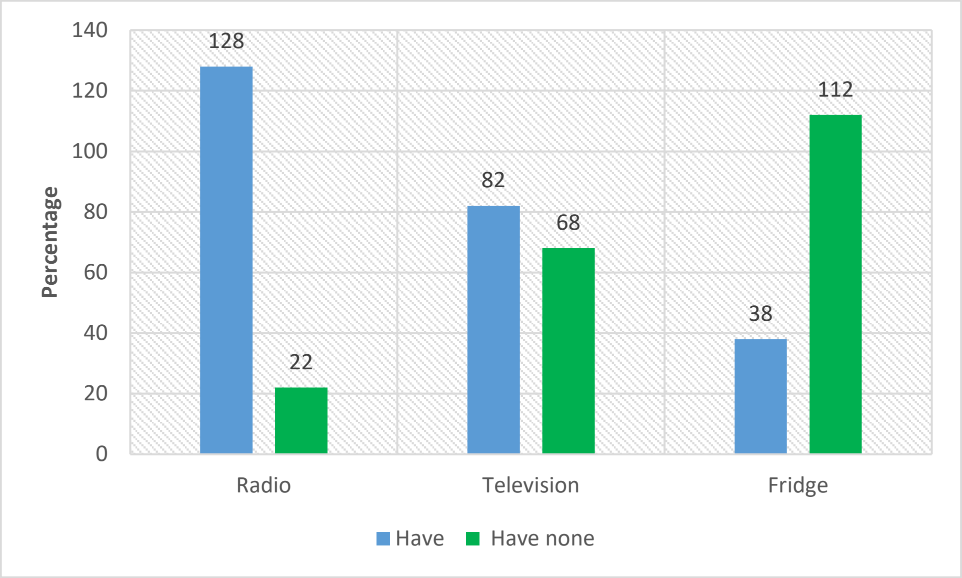


Figure 3-23: Ownership of household devices

Ownership of electricity powered devices among the grid connected farmers is presented in the Figure 3-23. While 128, 82 and 38 respondents reported having radio, television and fridge respectively. This indicate a per household-device ownership percentage of 85%, 55% and 25% for radio, television and fridge respectively.

3.2.5 Projected domestic electricity demand (off-grid farmers)

The domestic energy requirement by rural households is for lighting, heating, cooking and powering of domestic devices such as radio, mobile phones, television, fans etc. The daylight period of the study area is about 12 hours (Parker and Diop-Kane, 2017). Therefore, based on the type of house currently being used by the farmers and the electricity consumption pattern observed from the grid-connected rural dwellers during the field work. The following rural household electricity consumption is proposed. The units of devices recommended is similar, the only different is that energy efficient devices are proposed to be used by the household. This would not only conserve energy but would enable more farming households to be served. Thus, electricity consumption of households involves four energy efficient 20 W compact florescent bulbs which is to be used for 12 hours between 19pm to 6am. An 80 W Liquid Crystal Display television for 6 hours. The time usage of television is traditionally for 2 hours in the morning (6-8am) before leaving for farm and 4 hours in the evening (6-10pm) before people go to sleep. An average Nigerian household has transistor radio which is usually runs on lead battery (Akinyele and Rayudu, 2016). Thus, just like television, a 10 W transistor radio is projected to be used for 9 hours/ day. First, 6am to 9am in the morning and 18pm to 22pm at night. Two 30 W ceiling fans are also to be used for 12 hours/day (6pm to 5am). Importantly, some family members are likely to be at home during the day especially the petty traders. Therefore, a 100 W base load per rural household is projected. This is also to be used for miscellaneous electricity driven devices such as phones and rechargeable lamps. The above data is used to evaluate the household load profile presented in the **Error! Reference source not found.** and **Error! Reference source not found.**.

However, as noted in the section 3.2.4.4, only 25% of the grid connected rural households have fridge. Two scenarios are therefore proposed in the estimation of the daily energy demand of the farmers shown in the Table 3-2. The scenario shown in the **Error! Reference source not found.** assumes that rural households have the aforementioned without fridge. The second scenario (**Error! Reference source not found.**) assumes that households, in addition to the aforementioned, have one 150 W fridge which is used for 7 hours a day. It is therefore switched on when farmers are leaving home for the farms at 9.00 in the morning and switched off at 17.00 when farmers are returned in the evening.   As shown in the **Error! Reference source not found.**, a typical Nigerian household has two peak periods of electricity consumption (Adeoti et al., 2001b; Ogbonna et al., 2011; Akinyele and Rayudu, 2016; Akinyele et al., 2015;Adaramola et al., 2014). The first being between 6am to 9am usually for lighting, cooking and utilization of electronic devices. The second peak period is the evening when people are returned from work till 22pm when people sleep. Hence, the peak and base power demand per household is 330W and 100W respectively. Importantly, the projected 2.250 kWh electricity consumption per household per day is within the range of 1- 3 kWh/ day reported for rural households from earlier empirical studies conducted across different parts of Nigeria (Adaramola et al., 2014; Adeoti et al., 2001b; Ogbonna et al., 2011).

Table 3-2: Daily electricity estimates for the farmers

Load purpose	**Numbers**	**Power (W)**	**Hours**	**Consumption (Wh/day)**
Lighting (CFL)	4	20	12	960
Television	1	80	6	480

Radio	1	10	9	90
Ceiling fan	2	30	12	720
Fridge	1	150	24	3600*
Total		**2250/5850 (Wh/day)**		

*Currently used by only 25% of the grid connected farmers.

3.2.6 Estimation of Cooking Biogas Demand

In this section, the quantity of biogas that would be required to replace fuelwood and kerosene for cooking is evaluated. As noted in the sections 3.2.3.2.1 and 3.2.3.2.1 about 9.91 kg and 0.215 L of fuelwood and kerosene respectively are being consumed daily by the households. Meanwhile, in their study of 3000 households across Sub-Saharan African region, Adkins et al (Adkins et al., 2012) reported that 80% of the rural household kerosene consumption is for lighting while 20% is used for cooking. Therefore, household's daily kerosene used for cooking is 0.043 L.

The total useful energy from the fuels is calculated from the lower heating values and the efficiencies of heat generations from the fuels (Gujba et al., 2015) using equation 3.1

$$U_E = \left[\left(M_{kerosene} * LHV_{kerosene} * \eta_{kerosene} \right) + \left(M_{fw} * LHV_{fw} * \eta_{fw} \right) \right] \qquad (3.1)$$

Where U_E is the useful energy used for cooking (kJ/day); $M_{kerosene}$ is the daily mass consumption kerosene in (kg/day); M_{fw} is the daily mass consumption of fuelwood in (kg/day); $\eta_{kerostove}$ is efficiency (%) of heat generation from the kerosene stove; η_{fw} is efficiency (%) of heat generation from the fuelwood stove while $LHV_{kerosene}$ and LHV_{fw} represent low heat values (kJ/kg) of kerosene and fuelwood respectively. The efficiencies of heat generation used are 14% for fuelwood stove (Ballard-Tremeer and Jawurek, 1996) and 55% for kerosene stove (Gujba et al., 2015). Biogas is expected to replace both fuelwood and kerosene currently being used for cooking. Therefore, the useful energy provided by both kerosene stove and fuelwood must be the same as the useful energy provided by the biogas burner. Thus, the daily biogas required is obtained from equation 3.2.

$$M_{biogas} * LHV_{biogas} * \eta_{biogas} = \left[\left(M_{kerosene} * LHV_{kerosene} * \eta_{kerosene} \right) + \left(M_{fw} * LHV_{fw} * \eta_{fw} \right) \right] \qquad \textit{(3.2)}$$

Where M_{biogas}, $M_{kerosine}$ and M_{fw} are the masses (kg/day) of biogas, kerosene and fuelwood respectively; LHV_{biogas} , $LHV_{kerosene}$, LHV_{fw} are the low heat values (kJ/kg) of biogas, kerosene and fuelwood correspondingly while η_{biogas}, $\eta_{kerosene}$, η_{fw} are the thermal efficiencies of biogas burner, kerosene stove and traditional three stone fuelwood stove respectively. The efficiency of heat generation from biogas stove is 45% (Shrestha, 2001). The parameters used to calculate daily biogas demand by the rural household is summarised in the Table 3-3.

Table 3-3: Parameters for daily biogas demand estimation

	Fuelwood	Kerosene	Biogas
Low heat value (kJ/kg)	10,720	42, 380	18,726*
Density (kg/m^3)	-	820	1150
Efficiencies of heat generation (%)	14	55	45

*percentage methane content assumed 60% since the raw biogas is to be partially cleaned to remove some CO_2.

Using these data, the daily biogas required per household is calculated as 1.65 m^3 which results in 0.305 m^3 biogas per capital per day. This value falls within the range of earlier studies on the required cooking energy in the rural communities. Shaaban and Petinrin, (2014) estimated 0.3 m^3 per capita biogas requirement per day for rural household while Abila, (2014) projected 0.425m^3/person/day. Besides, the per capital daily biogas requirement for cooking by rural households in Uganda (Orskov et al., 2014), Indian (Rai, 2002) and Bangladesh (Rahman et al., 2014) had been estimated as 0.380 m^3, 0.227m^3, and 0.333m^3 respectively.

3.2.7 Estimation of Farming Energy Demand

At the moment, there is no data or reported work on the quantification of energy demand for drying per Nigerian rural household. Thus, the required energy for drying per rural houshold is estimated base on the following:

- Farm size
- Crop cultivated
- Processing system or requirements.

According to the survey, the average farm size within the study area is 2.7 ha/farmer. Based on the Figure 3-10, the four most cultivated crops are cassava, maize, tomato and cashew with the size shared presented in the Table 3-4. However, cashew is a perennial crop and harvesting is done during the dry seasons. Thus, special drying of the nuts is not required.

Table 3-4: Current land share of the most cultivated crops

Crop	Land share (ha)	Number of times planted/year
Cassava	1.579	1
Maize	1.077	2
Tomatoes	0.769	2
Cashew	0.486	Perennial

The following assumptions are made at calculating the required energy demanded for the drying:

- That the farmers maintain the current farm size and area cultivated per crop.
- Drying of cassava is assumed to be for cassava cake (used for processing of gari, tapioca, lafun and high quality cassava flour).
- The moisture content (wet base) of the cake is 40% while flour is 10%.
- The moisture content (wet base) of maize from field is 25% and usually dry to 12%.
- All tomatoes produced are cold stored before marketing.
- Maize and tomato are intercropped with cassava tradition in Nigeria (International Institute of Tropical Agriculture, 2010);(Adeniyan et al., 2014) and currently being practised by the farmers.
- That the farmers maintain the current tradition of mixed cropping system.
- Specific heat capacity of water is 4.2 kJ/kg/k
- Latent heat of vaporization of water is 2,260 kJ/kg
- Average atmospheric temperature is 25^{0}C.

As reported by (FAOSTAT, 2017), Table 3-5 shows area planted, production and yield for the selected crops for Nigeria in 2014

Table 3-5: Nigeria's crops production and yield per hactare in 2014.

Crops	Area planted (ha)	Production (tonnes)	Yield (tonnes/ha)	Household production/yr. (kg)
Cassava	7,102,300	54,831,600	7.720	12,190*
Maize	5,849,800	10,790,600	1.850	3,990*
Tomato	541,800	2,143,500	3.956	6,084*
Cashew	380,744	894,368	2.349	1,142*

*Calculated from Table 3-4.

3.2.7.1 Heat required for drying

From Table 3-5 about 12,190 kg of cassava is to be dried per household per year. Therefore, the required water to be evaporated is calculated from equation 3.3 (Earle, 2004; Kemp, 2007a)

$$M_w = M_{Cassava}\left(M_i - M_f\right) \qquad (3.3)$$

Where M_w, $M_{Cassava}$, M_i, and M_f masses (kg on wet bases) of water, cassava, initial and final moisture content (%) of cassava respectively.

Total heat required to evaporate water is the sumation of the sensible heat required to boil the water and the latent heat of vapourisation and it is expressed in equation 3.4 (Serpagli et al., 2010).

$$H_{Total} = M_w\, C_p(T_d - T_a) + M_w\, H_V \qquad (3.4)$$

where H_{Total} is the total heat required in kJ/year, M_w is the mass of water, H_v represents the latent heat of vaporisation of water (2260 $kJkg^{-1}$), Cp is the specific heat of capacity of water (4.2 $kJkg^{-1 0}K^{-1}$) while T_d and T_a are the drying and ambient temperatures (^0C) respectively. The first part of the equation on the right side is the required sensible heat while the second part is the latent heat of vapourization. Drying of cassva was carried out at 65^0C with convective dryer. The average daily temperature and relative humidity of of the location are 25^0C and 80% respectively. An exhaust temperature of 40^0C was assumed and the required energy for drying was evaluated using psychrometric chart (Ian et al., 2012; Mujumdar and Law, 2010). Thus, the required heat for cassava drying is calculated to be 27,302.4 $kJday^{-1}$

which dries 33.4 kg of cassava per farmer. By tradition from the village, cassava processing is not done daily but forthnightly in larger quantity by the farmers. Besides, harvesting is done throughout the year but not at the same time or days. Thus, it is assumed that while dryer duty for cassava can be scaled up with 27,302.4 kJday^{-1}farmer^{-1}, a farmer can bring multiplier of 33.4 kg for drying since the current farm size and area cultivated per crop assumingly remained unchanged. For example, farmer A can bring 467.45 kg of cassava for forthnightly drying while farmer B can bring in 701 kg for drying every three weeks.

Similarly, heat required to dry maize is equally evaluated as 3577 kJday^{-1} while the total heat required for drying per household is 30,879.4 kJday^{-1}.

3.2.7.2 Heat required for cooling

Here the energy require for cooling of agricultural products of a typical household is estimated with the following assumptions:

- Tomato represents farmers' vegetable to be cold stored.
- The harvested tomato is refrigerated to control market influx during harvesting.
- Absorption chiller is used for the cold storage.
- Tomato is stored for two weeks at 12^{0}C (Díaz de León-Sánchez et al., 2009)

Quantity to be cooled = 6, 080 kg/household/year.

Hence, the required cooling demand per day (Q in kJday^{-1}) is evaluated from equation 3.5

$$Q_{cold} = M_w \, C_{Pw}(T_{st} - T_{amb}) + M_{Tm} \, C_{PTm}(T_{st} - T_{amb}) \qquad (3.5)$$

where M_w and M_{Tm} are masses of produce per day (kgday^{-1}) of water and tomato respectively; C_{PW} and C_{PTm} are the specific capacities of (Jkg^{-1}K^{-1}) of water and tomato correspondingly while T_{st} and T_{amb} represent storage and ambient temperatures (^{0}C) respectively.

The ambient temperature of the studied location varies between 18^{0}C during hamattan periods and 30^{0}C during heat season but averaged 25^{0}C. To accommodate this variations the Logarithim Mean Temperature Difference method is adopted as indicated in the equation 3.6.

$$LMTD = \frac{(TS_H - TT_C) - (TT_H - TS_C)}{ln\left[\frac{(TS_H - TT_C)}{(TT_H - TT_C)}\right]} \qquad (3.6)$$

Where TS_H is the supply temperature of hot stream (C); TT_C is the target temperature of cold stream (C) ; TT_H represents the target temperature of hot stream (C) and TS_C is the supplied temperature of cold stream (C). The supplied temperature of ambient (TS_H) varies as noted above; the values are used to calculate the average Logarithim Mean Temperature Difference ($LMTD_{avg}$) and equation 3.5 is subsequently modified as:

$$Q_{cold} = M_w\, C_{Pw}\, LMTD_{avg} + M_{Tm}\, C_{PTm} LMTD_{avg} \qquad (3.7)$$

The specific heat capacity of tomato is taken as 3.98 kJ/kg$^{/}$K^{-1} while the moisture content of the predominantly grown local brid of tomato is 94.6% (Onifade and Aregbesola, 2013). Using equation 3.7, energy required for cooling per farming household is 957.80 kJday^{-1}. This represents daily cold-storing of 16.66 kg of tomato per farmer. However, market days within the area is five days interval and this tradition shaped harvesting of perishable agricultural products like tomato. So, during harvesting periods, vegetables are harvested every five days particularly a day prio to market day. Farmers also have preverence for different local markets. Hence, similar to the assumptions made for cassava, a farmer can cold-stored multiplier of 16.66 kg of tomato since the current farm size and area cultivated per crop assumingly remained unchanged.

3.3 Conclusion

In this chapter, the demographic statuss of the village has been highlighted. Household farm size was estimated to be 2.7 ha though it varries between 1.6 to 4.2 from densily populated southern part of the country to the large-land mass less populated Northern part of the country. Cassava, tomato, maize and cashew were identified as the major crops being grown in the community. The proportion of the farmers' land currently occupied by thsese crops had been used to evaluate farming energy requirement while questionnaire survey was adopted to elicite data used for the calculation of domestic energy requirements. Hence, the total energy demand per rural household per day is presented in the Table 3-6.

Table 3-6: Energy demand per rural households

Energy usage	Unit	Demand
Electricity	kWh	2250-3300
Drying	kJ/day	30,879.40
Cooling	kJ/day	957.8
Cooking	kJ/day	35,475.00

Chapter 4 : Evaluation of Post-harvest loss

4.0 Introduction

In addition to energy poverty currently being faced by the rural dwellers in the Sub-Saharan African countries as earlier established in the Chapter 2; heavy post-harvest (PH) is a common phenomenon particularly in Nigeria. Due to time constrain, it is very difficult to appraise the level of PHL of all crops being grown within the study area. A preliminary investigation was therefore conducted which reveals that tomato is one of most grown crops in the area. The investigation also shown tomato among crops with the highest postharvest handling challenges. It is therefore selected to be closely monitored for the PHL. The essence of the survey is also to compare the values obtained with the national data.

4.1 Methodology

The field survey for the post-harvest loss is carried out at Jagun village, Idere in Ibarapa Central Local Government area of Oyo state Nigeria. The village is purely an agrarian community with about 500 households living in about 200 houses and huts. The approach used for the field survey is divided into two: a) field study for the PHL waste evaluation; b) structured questionnaire survey for the post-harvest loss evaluation.

4.1.1 Field study for the PHL waste evaluation

Unit operations in the PHL handling of tomato as illustrated in the Figure 4-1 is divided into seven units. Matured but unripe tomatoes are picked from the farms and transported to the village on palm-front woven baskets. It is usually carried on head. Alternatively, 4-5 baskets could be stacked and transported to farmstead with motorcycle especially by the wealthy farmers. The baskets are then emptied into a bed made with grasses or leaves for about 2-3 days. The bed is usually under shield to reduce heat and evaporation during mulching. Sorting is done daily to remove broken or rotten tomatoes. Final sorting is then done during packaging where rotten or unripe ones are removed and discarded. Packaged tomato is then taken to the market. Occasionally, oversupply do occur during which what is taken to the market exceeds the demand by the traders that come from the city. In that case, farmers may be forced to return the tomato back to the farmstead with the expectation that there may be demand the following market. When this occurs, the produce must be kept longer which results in further rotten and sorting. The sorting done at this stage is classified as glutting. Sometimes, apart from selling at lower prices, the farmer may opt for selling the produce on credits while cases of abandonment do occur in some extreme instances, but this was not noticed during the survey. However, during the field work a 15 kg basket of tomato at the local market (Oja Oba) was sold at #1800 (£3.82) in July 2017 and later dropped to #500 (£1.06) by first week in September 2017.

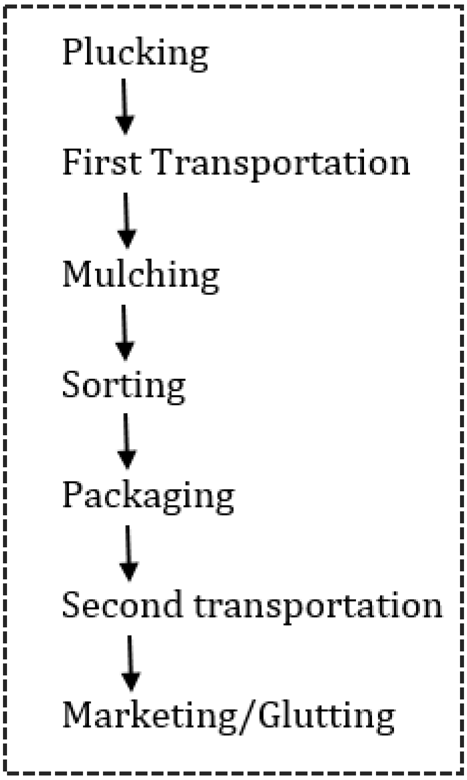


Figure 4-1: Unit operations in PH handling of tomato

Therefore, to evaluate the percentage PHL loss within the above value chain and considering the limited time and other resources, five volunteers' tomato farmers were randomly selected from the village and the PHL operations are monitored. This was done during the harvesting season of tomato between July and September 2017. The farmers were labelled A, B, C, D and E.

Quadratic sampling was adopted for the evaluation of tomato PHL. Thus, two quadrats of sizes 10.00m x 10.00m were randomly selected from the farms of each of the five tomato farmers. The quadrat is measured using wood pegs and measuring tape (Model: BMI EA53, China). Tomato harvested from each quadrat from the first to last plucking day was measured using weighing balance (Model: Hana, China) shown in the Figure 4-2 and the observed waste were evaluated against each of the farmer A to E in respect of the unit operations indicated in Figure 4.1. Microsoft Excel and the Statistical Package for Social Science (SPSS) are used for data recording and analysis respectively.

Figure 4-2: Weighing of tomato during plucking.

4.1.2 Questionnaire survey for the PHL loss evaluation

Through the help of a local teacher, a meeting was organised with the village head. The essence of the meeting is to inform them on the objectives of the research and the impact such findings can have on the wellbeing/agricultural activities. At the request of the village head, another meeting involving family heads was held during which September 22-24 was agreed for the administration of face-to-face questionnaire survey.

4.1.2.1 The Design of the questionnaire for the survey

The survey is interview ran questionnaire based. The presentation, language and structure of the questionnaire makes it easy to understand and requires less than 10 minutes to complete. Questions for the PHL is lumped in the same questionnaire used for the estimation of energy demand earlier explained in the Chapter 3. The last part of the questionnaire: section C seeks information on the PHL and farmer’s opinion on the proposed recommended technologies for the PHL loss abatement. Information sought in this section are the farm size, crops planted, numbers of times being planted, and the share of the farming land being currently occupied by different crops. Farmers perceived experience of crops wastefulness, the extent of wastefulness and its economic implications. Lastly, farmers are asked to give their opinion on the effect of electricity provision, drying facilities and cold room storage equipment on PH loss reduction.

4.2 Results and discussion

4.2.1 Tomato yield

The average yield of tomato in the study area is 3.562±0.089 tons/ha. The figure is less than the 3.915 tons/ha reported for Nigeria by (FAOSTAT, 2017). However, both cultivated area and yield of tomato in the south western part of the country where the study area belongs is lower compared to the Northern part of the country where above 4 tons/ha has been reported (Isah et al., 2014).

4.2.2 Estimated loss of tomato within the post-harvest value chain

Loss at each stage of the PHL handling operations by different farmers were expressed as percentage of the average yield per hectare as illustrated in the Figure 4-3. Farmers A, B, C, D, E represent each of the farmers randomly selected for the PHL evaluation of tomato crops. Plucking, mulching, sorting and glutting are as explained section 4.1.1. However, freshly harvested tomato is first transported from the field to farm-shed. Farm-shed is usually located at the backyard of the village house. This is to make daily sorting easy especially since it is usually handled by women or children during their spare times. Transferring it to the village also makes packaging and eventual transportation to market easy. Transportation to market is usually handled by commercial vehicles from a pre-determined pickup point in the village. Hence, the first transportation from farm to the farm-shed is depicted as “Transportation1” while the second movement from the village pickup point to the market is designated as “Transportation2”. Sometimes farmers are unable to sell the produce on the market day and the produce are returned to the farm-shed, sorted and repackage for the next market. Loss at this stage is designated as “Glutting”

Figure 4-3: Tomato wastage during PHL handling operations.

As shown in the figure, market glutting (13.3%) is responsible for the highest cause of PHL loss of tomato. This could be attributed to the prolonged and unavoidable keeping of tomato produce by the farmers. Tomato are usually transported to the market with open trucks as indicated in the Figure 4-4 during which it is exposed to harsh conditions which aid deterioration of the produce. Hence, by the time the produce is transported to and from the market in such condition, more than half of the content would have been wasted.

It is followed by sorting with accounts for 8.14% of the loss. However, the bulk of the unfit tomato are not always discarded as the farmers usually remove and preserve the seeds for the subsequent planting. Transportation accounts for about 4.5% of the loss which is in line with between 2.7 to 15 % transportation induced loss of tomato reported in the literature (Abubakar and El-Okene, 2015;Adeoye et al., 2009).

Figure 4-4: Tomato truck arriving local market (Abubakar and El-Okene, 2015)

4.2.3 Farmers' perception of crop wastage

Table 4-1: Farmers' perception on crops wastage

Crop	Most wasted	2nd wasted	3rd wasted	4th wasted	5th wasted	6th wasted	Least wasted
Cassava	0	4	44	56	2	0	0
Yam	0	2	54	44	0	0	0
Maize	0	94	0	6	0	0	0
Tomato	98	0	0	0	0	0	2
Melon	0	0	0	2	72	24	2
Cocoa	0	0	0	0	2	52	46
Cashew	0	0	0	0	2	52	46

A seven-scale ranking was adopted to understand farmers perceptions and experience regarding crop wastage. The essence is to enable farmers to rank the wastefulness from the most wasted to the least wasted. On this scale 1 indicates first most wasted crop, 2 the 2nd most second wasted crop; 3 as the 3rd most wasted crop; 4 as the 4th wasted crops; 5 indicating 5th wasted crops; 6 representing 6th wasted and 7 indicating least wasted crop. . Presented in the Table 4-1 is the farmers' perception. About 98% of the farmers believe that tomato is the most wasted crop. This is closely followed by 94% who felt that maize is the second most wasted crop. About 54%; 56% and 72% of the farmers believe that yam, cassava and melon are the third, fourth and fifth most wasted crops respectively. Additionally, the waste on cashew and cocoa is generally regarded as small. This is probably the harvesting times of these tree crops usually fall on dry season when sun-drying is not challenging.

4.3 Conclusion

About 31.3% estimated at 1.01 to 1.16 tons of tomato is being lost per hectare during the postharvest handling operations. This is below between 50% and 90% PH loss reported for tomato. However, this sharp decrease could be attributed to the recent adoption of improved seedlings that is characterised with lower moisture content and thicker outer layers(Toillier and de Bellaire, 2017). Most of the available data on tomato were published more than a decade ago when traditional tomato seedlings with about 95% moisture were predominantly planted. Notwithstanding the differences, PHL of one-third of agricultural produces is quite enormous and possess great challenge to food security while leaving the farmers on continuous abject poverty. Hence, a solution is needed for a reliable and affordable solution to the PH waste.

Chapter 5 : Design and Modelling of the system

5.0 Introduction

Having evaluated rural household's demand of energy for electricity, cooling, cooking and drying of agricultural produce in Chapter 3 and extent of PHL wastage in the Chapter 4, in this chapter, details of design parameters, material selection and modelling approach for the CCHP system is highlighted. The designed CCHP unit is expected to meet the following conditions:

Table 5-1: Design considerations of the CCHP unit

Parameter	Expected conditions
Biogas	The fuel must be biogas
Energy Requirement	The users are agrarian rural community whose cooking, lighting, and drying energy requirements are to be fulfilled.
Farm residue	The system should be able to use both animal and crop farm residue as biomass substrates.
Sustainability	The model must be sustainable.
Ease of use	The user are mostly uneducated rural dwellers.
Availability	The system must have high availability
Affordability	The design must favourably compare to its close substitutes especially fuelwood, kerosene and cooking gas.

5.1 The design configuration

Following the above-mentioned conditions and the estimated energy demand together with biomass availability discussed in the Chapter 3, a biogas powered poly-generation system is considered. The poly-generation units - Figure 5.1 and Figure 5-2 are AD biogas driven system. Crop residue from smallholders' farmers are chopped to smaller units and mixed with source separated cattle market wastes. The mixture is then pre-treated (70^{0}C for 1 hr with sodium carbonate). The mixture is then cooled to the digestion temperature (35^{0}C) and sent to the digester. The produced biogas is temporarily stored in the biogas tank. It is then divided into two streams. One part is cleaned and used to power an ICE which produces electricity for the village. Two approaches were investigated for the heat recovery from the exhaust gas using two heat exchangers. In the first configuration (Figure 5.1) The first air-air heat exchanger which recovers heat from the exhaust and use same to power convective tray dryers for drying of agricultural products. The second heat exchanger is a gas-liquid exchanger with remove heat from the engine exhaust and use same to power the desorber of the LiBr-water absorption chiller. In the second configuration (Figure 5.2) the first heat exchanger recovers heat from the exhaust and use same for water heating. The generated hot water is subsequently used for the drying

Therefore, on the bases of above conditions, the design parameters and material selection for the anaerobic digester, cleaning devise, ICE, heat exchangers, dryer and cold store would be discussed.

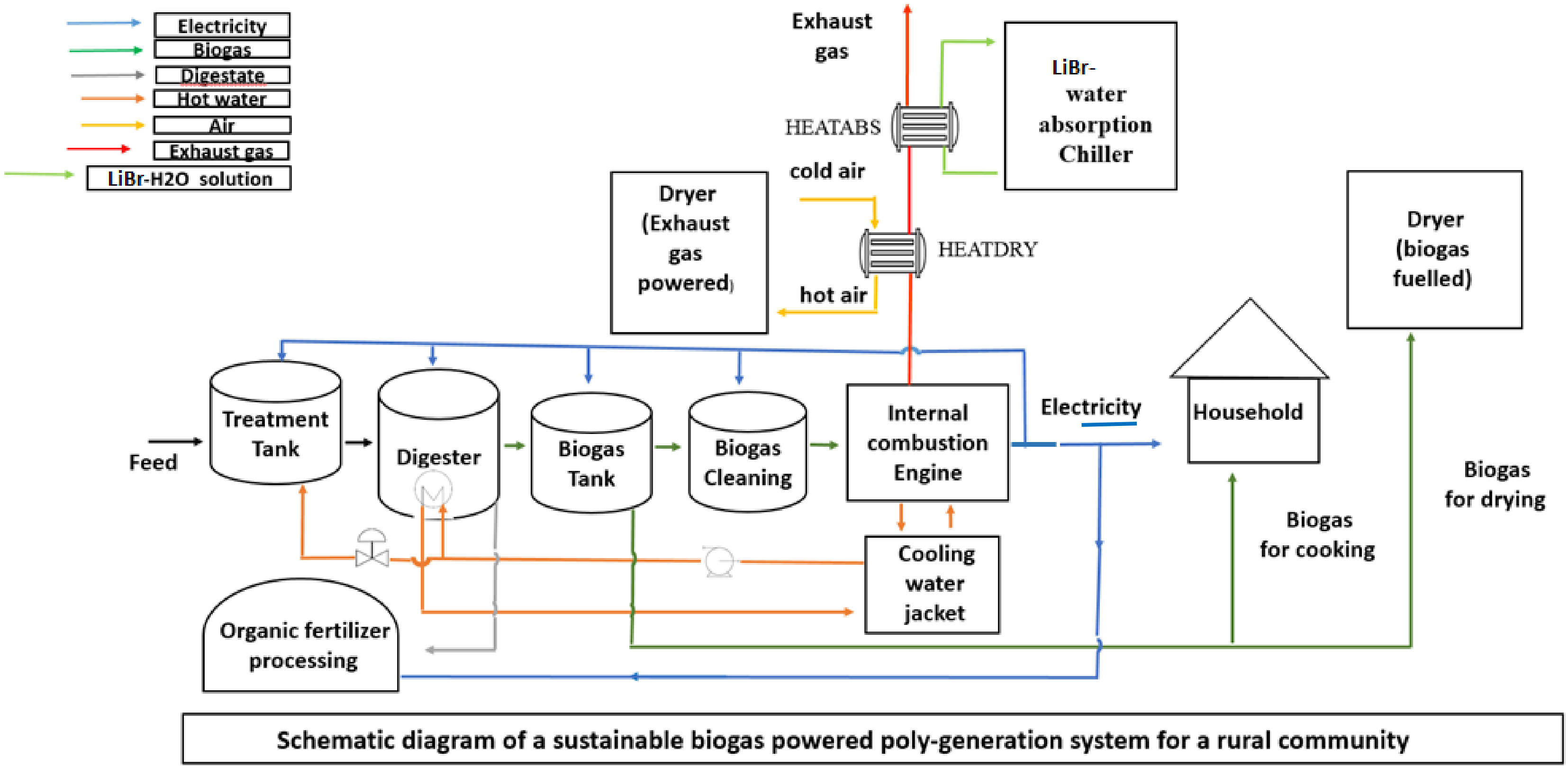


Figure 5-1: Schematic diagram of a sustainable biogas powered poly-generation system for a rural community

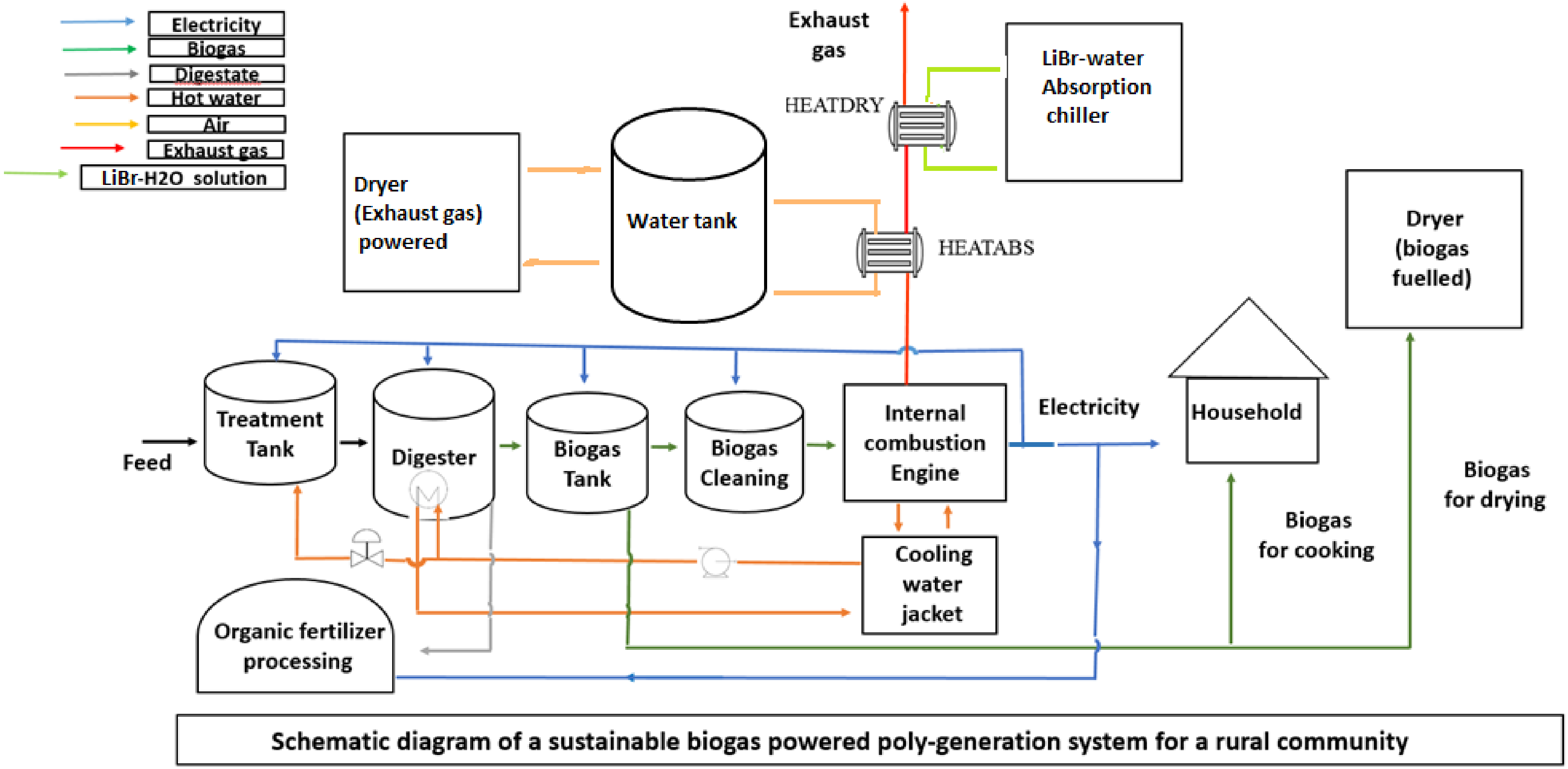


Figure 5-2: Schematic diagram of a sustainable biogas powered poly-generation system for a rural community (storage tank inclusive)

5.1.1 Digester design

The available daily crop residue is 43,889.5 kg/day with the features presented in the **Error! Reference source not found.**. Thus, the average moisture content and total solids is taken as 54.37% (wet bases) and 45.63% respectively. Hence, crop residue to water ratio of 1: 4.6 is adopted to obtain a 10% total solid in the digestion system since AD process has been reported to perform well with TS less than 15% (Nguyen et al., 2014; Rowse, 2011). Therefore, the daily feedstock available feedstock is 194 m^3/day and the hydraulic retention time (HRT) of 28 days is assumed. Details of these assumptions are explained later in the section 6.3. Hence, the required digester volume Vr is calculated from equation 5.1

$$HRT = \frac{V_R}{V} \qquad (5.1)$$

Where HRT is the hydraulic retention time (day); V_R is the reactor volume (m^3) and V is the daily influent rate (m^3/day). This gives reactor volume of 6,000 m^3 including the additional 10% gas holding and missing volume.

Meanwhile, for ease of operation and handling of digestate, the required digester volume is divided into 5 of 1200 m^3. The reactors are assumed cylindrical with height to diameter ratio of 2 [12] while the calculated area per digester is 656.4 m^2. A rigid domed Chinese digester (Figure 5.3) is considered. This is because it is a matured digester and can be constructed by the local bricklayers with bricks and concrete. Traditional Chinese digester is both self-heating and unmixed. However, to increase the efficiency of the digester, it is modified to include these two important features.

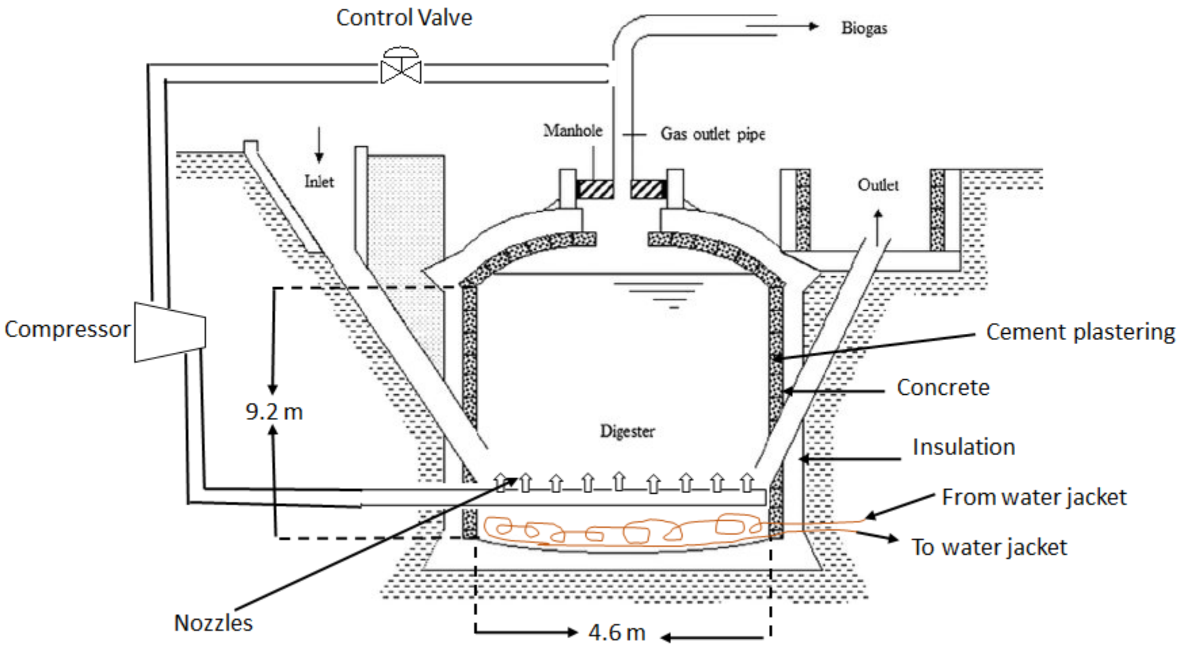


Figure 5-3: Modified rigid domed Chinese digester

5.1.1.1 Heating of digester

Estimation of heat balance for AD system is based on the following heat requirements: (1) Heat required to warm substrate from atmospheric temperature i.e. 25°C to operating temperature i.e. 35°C; (2) Heat loss by radiation, convection and conduction; (3) Reaction heat from biochemical activities of reactor's microorganisms.

The required heat for substrate warming up (kW) is estimated using equation 5.2:

$$Q_{\mathrm{wm}} = (M_{\mathrm{sb}} \times C_{\mathrm{p}} \times \Delta T)/3600 \tag{5.2}$$

Where M_{sb} is mass of substrate (kg·h^{-1}); ΔT is difference between ambient and digestion temperature; C_{p} is specific heat capacity of substrate (kJ·kg^{-1}· $^{\circ}$K^{-1}) while 3600 is the conversion unit from kJ/hr to kW.

Heat loss by radiation (kW) is evaluated according to equation 5.3:

$$Q_{\mathrm{Rad}} = \varepsilon * \sigma * (T_{\mathrm{d}}^{4} - T_{\mathrm{amb}}^{4}) * \frac{A_{\mathrm{dr}}}{1000} \tag{5.3}$$

Where ε is emissivity (-) of the outer brick wall; σ is Stefan-Boltzmann constant (Wm^{-2}K^{-4}), A_{dig} is area of the digester (m^{2}); T_{d} and T_{amb} are digestion and ambient temperatures (K), respectively, while 1000 is the conversion factor from W to kW.

AD encompasses some natural biochemical reactions. Some are endothermic while others are exothermic. Disintegration of protein is usually endothermic while fragmentation of lipid and carbohydrate molecules tend to be exothermic (Lindorfer et al., 2006). These will be represented with change of enthalpy as illustrated in the equations 5.4-5.6. From these equations, biochemical heat can be evaluated from proximate composition of feedstock.

$$\mathrm{C_6H_{12}O_6} \rightarrow \mathrm{3CO_2 + 3CH_4} \qquad \Delta H_R^0 = -138.5\ \mathrm{kJ \cdot mol^{-1}} \tag{5.4}$$

$$\mathrm{C_3H_7NO_2 + 2H_2O} \rightarrow \mathrm{3CO_2 + 3CH_4 + 2NH_3} \qquad \Delta H_R^0 = +198.5\ \mathrm{kJ \cdot mol^{-1}} \tag{5.5}$$

$$\mathrm{C_{16}H_{12}O_6 + 14H_2O} \rightarrow \mathrm{9CO_2 + 22\ CH_4} \qquad \Delta H_R^0 = +544.5\ \mathrm{kJ \cdot mol^{-1}} \tag{5.6}$$

The digester is insulated with 0.2-meter polyurethane foam which has a thermal conductivity of 0.026 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. Air gap between the materials makes heat loss through convection negligible while conductive heat loss through insulation material is evaluated as shown equation 7 (Thirugnanasambandam et al., 2010).

$$Q_{\mathrm{ins}} = \frac{(T_{\mathrm{d}} - T_{\mathrm{amb}})}{\frac{1}{A_{dig}}\left(\frac{S_{\mathrm{ins}}}{k_{\mathrm{ins}}}\right) \times 1000} \tag{5.7}$$

Where Q_{ins} (kW) is heat lost through insulator; T_{d} is digestion temperature (K) ; S_{ins} is insulator's thickness (m); k_{ins} is thermal conductivity of insulator ($\mathrm{Wm^{-1}K^{-1}}$) and $\mathrm{A_{dig}}$ is the area of the digester while 1000 is the conversion factor from W to kW.

Hence, the total heat required for the digestion system is evaluated as defined in the equation (5.8)

$$Q_{dig-total} = Q_{\mathrm{wm}} + Q_{\mathrm{Rad}} + Q_{\mathrm{ins}} \tag{5.8}$$

Where $Q_{dig-total}$ is the total heat required for digestion (kW), $\mathrm{Q_{wm}}$ is the required heat for substrate warming up (kW); $\mathrm{Q_{rad}}$ is the heat loss (kW) through radiation while $\mathrm{Q_{ins}}$ is the heat loss (kW) through insulator. Hence, considering the above, it is estimated that about 54.6 kW of heat would be required for the maintenance of the AD process.

Heating of the digester is provided by the hot water from cooling jacket which leaves at 85^0C and returned at 65^{0}C. A type L flexible 15 mm copper tube with 2mm thickness is selected for the heating. Since the required heat is known, the flowrate of hot water through the pipe is estimated from:

$$Q_{dig-total} = MC_{pc}(T_2 - T_1) \qquad (5.9)$$

Where $Q_{dig-total}$ the required heat (kJ/hr) by the digestion system, M is the mass flowrate of water in kg/s, C_{pc} is the specific heat capacity of copper (J/kg/K), T_2 is exiting temperature (K) of hot water while T_1 is the returning temperature (^{0}K). More so, since the pipe is cylindrical, the required length of copper pipe to transfer the required heat is calculated from equation 5.10 (Kakac et al., 2012).

$$Q_u = -kA\frac{dT}{dr} = 2\pi\frac{k(T_1 + T_d)}{ln\left(\frac{r_2}{r_1}\right)} \qquad (5.10)$$

Where Q_u is the heat transfer per unit length of the material (kW/m), k is the thermal conductivity of copper (W/mK), T_1 is the returning temperature of hot water while T_d is the digestion temperature (K). More so, r_2 and r_1 symbolises the external and internal diameter of the pipe respectively while A is the area per unit length (m)

5.1.1.2 Mixing of digester

Mixing is the process by which inhomogeneity of a process is reduced to achieve a desirable result. Non-uniformity of a system can be in the form of concentration, phase or temperature differences which need to be reduced to achieve the desired reaction and products in AD process. In the case of AD, mixing is essential to achieve the following (Sindall, 2014): a) it brings microorganisms in contact with nutrients; b) reduces formation of scum or grits and c) creates process homogeneity by decreasing Ph, temperature and concentration gradients. Generally, mixing has been shown to increase both quality and quantity (Lin et al., 2014) of biogas generation.

Mixing of AD can be achieved through mechanical, gas or recirculation system. Of these, mechanical mixing is the most energy efficient (Wu, 2010) but predisposed to system break down and high cost of maintenance while recirculation is the least efficient. Gas mixing is cheaper to maintain and can be used to achieve similar mixing effectiveness with the mechanical mixing. It is therefore adopted in this study. Gas mixing involves collection of biogas from the top and pumping it through reactor from the bottom using nozzles. This results in the formation of bubbles which subsequently transmit momentum to the surrounding fluid. Transferring of momentum is as a result of the thrust which bubbles exerted on the surrounding liquid which led to turbulence effect occurring from the low-pressure region produced by the movement of the bubbles. Mixing from the bottom of the reactor has been shown to significantly increase the production of biogas (Ong et al., 2002). Gas mixing of the digester is modelled following the earlier studies reported by (Dapelo, 2016; Sindall, 2014 and Wu, 2010) with the following features:

Table 5-2: Features of the digester for gas mixing

Particular	Unit	Value
External diameter	m	4.6
Height of digester	m	9.2
Maximum gas flow rate per nozzle	ms^{-1}	$4.717\ 10^{-3}$
Number of nozzles		10
Distance of the nozzle from the bottom	m	0.3

From the above table, the power input per unit (E_{in}) of the nozzle can be determined from (Wu, 2010).

$$E_{in} = P_1 Q_{bm} ln\left(\frac{P_2}{P_1}\right) \qquad (5.11)$$

Where $Q_{bm}$is the volumetric flow rate required for mixing (m^3hr^{-1}), P_1 is the absolute pressure (Jm^{-3}) at the surface (atmospheric pressure), and P_2 is the absolute pressure (Jm^{-3}) at the nozzle. P2 is evaluated as illustrated by the equation (5.12)

$$P_2 = P_1 + \rho g H \qquad (5.12)$$

Where ρ symbolises density of the sludge (kgm^{-3}), g is the acceleration due to gravity (Nkg^{-1}) while H represents the height (m) of the digester. From the values presented in the Table 5.2; the power input proportionate to the maximum mixing flow rate is 2.15 Wm^{-3}.

In order to determine the flow parameter, a dimensionless set β which is a function of the gas flow rate and digester volume could be defined (Dapelo and Bridgeman, 2018).

$$\beta = q^2 g^{-1} {V_R}^{-\frac{5}{3}} \qquad (5.13)$$

Where q is the total gas flowrate (m^{3}hr^{-1}), g the acceleration of gravity and V_R the reactor volume (m^3). Therefore, for a reactor volume of 1200m^3, a value of 243.6 LS^{-1} is estimated for a mixing power of 2.15 Wm^{-3}.

The above total volumetric flowrate and parameter of biogas presented in the Table 5.2 was used to determine the power requirements of the mixing compressor. Since the initial pressure (P_1) and discharge pressure (P_2), as estimated from equation (5.12) are known parameters, a mechanical efficiency of 0.85 was assumed to determine the compressor power requirement using Aspen Plus (details in section 5.3) and a value of 461W was obtained.

5.1.2 Biogas Cleaning Configuration

Thorough cleaning of the biogas is not required as the chosen prime mower is designed to work with low grade biogas of about 67% methane content. Hence, a small pack-bed water scrubbing unit with the working principle illustrated in the Figure 5-4 is considered. The system takes advantage of difference in solubilities of both CO_2 and CH_4 at elevated pressure. Pressurised raw biogas is counter-currently passed through pressurised water droplets in a packed-bed column. At the elevated pressure CO_2 solubilises in water and got removed. Hence, the biogas is enriched. The CO_2 liquid is first flashed where part of the entrapped methane is removed. The liquid is then passed through the second column (stripper) where pressurised air is used to for the regeneration of water. Based on the experience from local market and literature, a scrubber of 3.0 m height and 0.3 m diameter is considered (Magli et al., 2018;Ullah et al., 2017;Shaw and Nagarsheth, 2015)

To achieve the projected biogas purification the required water flowrate, number of column stages and working pressure must be determined. The required energy also needs to be evaluated. Hence, the entire system including the absorption tower, compressors and stripping tower was modelled with Aspen Plus. The model is then validated with experimental data from Ray et al.(2015) and Nock et al.(2014).

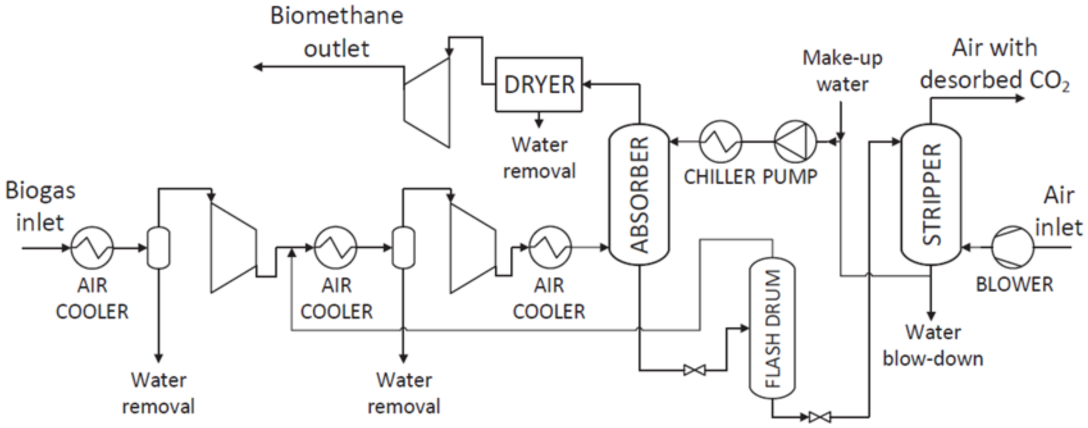


Figure 5-4: Schematic of biogas water scrubbing [(Magli et al., 2018)

5.1.3 Prime Mover Selection and Specification

The selected reciprocating internal combustion engine are biogas powered 72kWe (G3306, Caterpillar Inc.) and 103kWe (G3406 Caterpillar Inc.) engines. Details of the rational for the choice and specifications are discussed in the section 6.2.2.

5.1.4 Heat Exchanger

Two heat exchangers (**Error! Reference source not found.**) are used within the system; one for the heat recovery from the exhaust for drying (HEATDRY) and the second for the heat recovery from the exhaust for the driving of absorption chiller (HEATABS). The design ensures that exhaust exits HEATDRY with 180^0C while it leaves the HEATABS at 120^0C to avoid precipitations which might lead to the rusting of exhaust pipes (Pierce et al., 2019; Kass et al., 2005). Since these exit temperatures are known and Aspen Plus was able to calculate the duty of the heat exchanger while logarithm mean temperature differences were used to evaluate the required areas of the exchangers. HEATDRY is a gas-gas heat exchanger while HEATABS is a gas-liquid heat changer. So, the geometries and the overall heat transfer coefficients (U) considered are as suggested by (Sadik Kakac et al., 2012)

The duty of the heat exchanger is calculated as:

$$Q_{hex} = UA\Delta T_{LmTD} \tag{5.14}$$

$$T_{LMTD} = \frac{(T_{h1}-T_{c2})-(T_{h2}-T_{c1})}{ln\left(\frac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}}\right)} \tag{5.15}$$

Where Q is the duty of heat exchanger in W, U is the overall heat transfer coefficient (W/(m^{2}K), A is the area of the heat exchanger (m^2) while T_{h1} and T_{h2} are the inlet and outlet temperatures of hot fluid respectively and T_{c1} and T_{c2} also represent inlet and outlet temperatures of the cold fluid respectively. The cost (USD/m^2) of heat exchangers are sourced from online.

5.1.5 Dryer configuration

The dryer considered in this work is the Atesta dryer (Figure 5-5) which is a cross flow convective cabinet dryer predominant in the Sub-Saharan African region (Boroze . et al., 2014). It is propane driven and usually made with plywood while the drying trays are made with wood and wire mesh. Details of its features are presented in the Table 5-3.

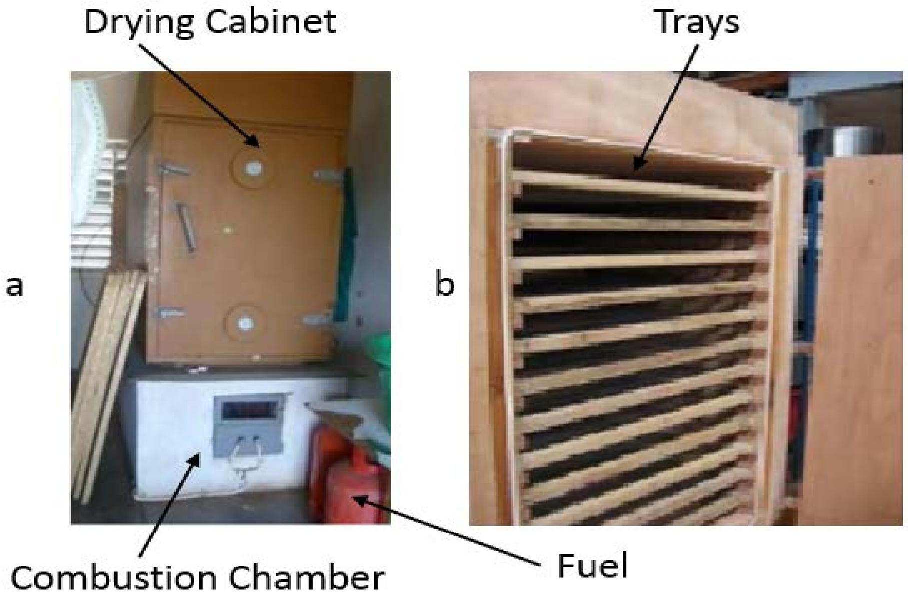


Figure 5-5: Atesta dryer (Desmorieux, 2012)

Table 5-3: Features of Atesta dryer

Particulars	**Features**
Energy source	Propane – 0.5 kg/hr
Drying time	24 hrs

Drying temperature	70-90 C
Operation mode	Batch
Capacity	100 (kg/batch)
No of trays	20
Single tray area	0.84 m2
Total tray area	16.80 m2
Life span	10 years
Materials used for construction	Masonry, wood and metal sheet
Products	Agro products.

5.1.6 Cold storage configuration

The chiller used in this study is a 3 tons hot water fired absorption chiller details of which is presented in section 5.3.3. The dimension of the cold storage modelled is 6 m×5 m×2 m with 1 m peak for the roofing as indicated in the Figure 5-6.

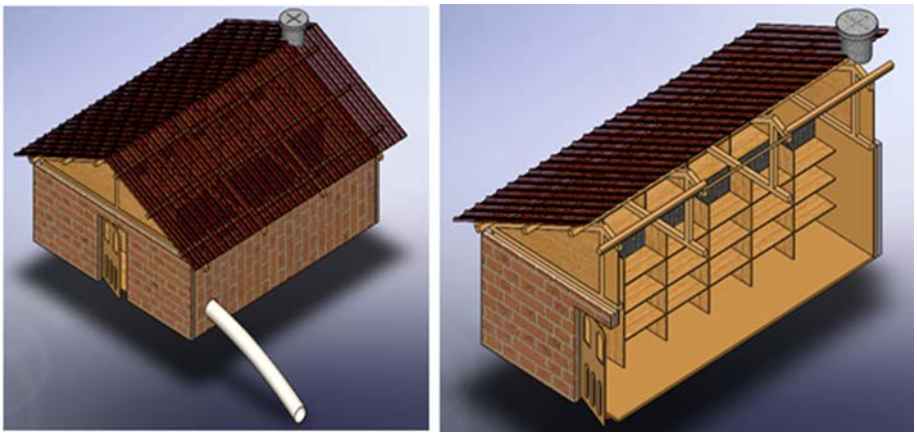


Figure 5-6: Design of the cold storage

It is made up of wood pine, corkboard and concrete as inner layer, insulator and outer layer respectively as illustrated in Figure 5-7. The adopted thickness are 12 mm, 70.5 mm and 101.6 mm for pine, corkwood and brick, respectively (being the thickness of these materials available in the local market). Cold air is blown across the stored produce, which carries away heat of respiration as well as heat absorbed from the surrounding to maintain internal temperature at 15^{o}C which is the storage temperature for most living tissues to avoid chilling injury which can lead to softening of the farm produce. Chilled water at 7.5^{0}C produced from the absorption chiller is circulated through the cold storage which serves as the evaporator. The water exits at 12.5^{0}C and returned to the Chiller.

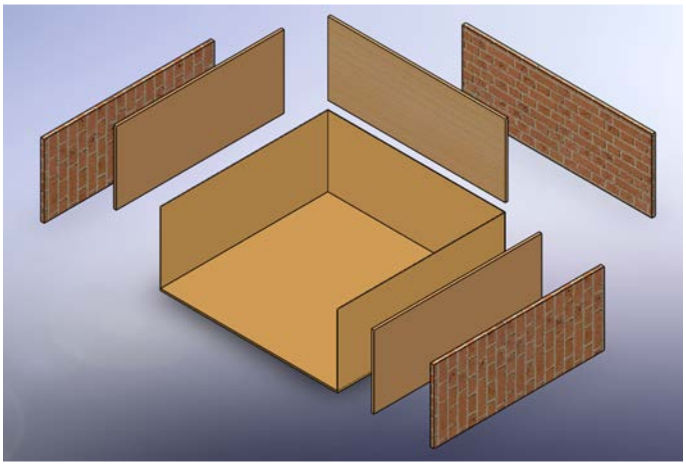


Figure 5-7: Materials of cold room construction

The required cooling load is evaluated for yam storage which is a popular tuber crops being cultivated across the country. The load is defined as shown in the equation 5.16

$$Q_{storage} = Q_{sensible} + Q_l + Q_{res} \tag{5.16}$$

Where $Q_{storage}$ is the required cooling load in kW, Q_s (kW) symbolises sensible cooling load, which is the heat required to cool yam tubers from ambient temperature to storage temperature. Q_l (kW) is the heat loss from cold room, while Q_{res} (kW) is the respiratory heat generated by yam tubers which must be carried away.

Yam tuber comprises of both moisture and dry matter which partake in cooling and heating processes. Hence, the sensible cooling load is defined as in equation 5.17

$$Q_{sen} = M_w C_{pw}(T_{amb} - T_{st}) + M_y C_{py}(T_{amb} - T_{st}) \tag{5.17}$$

Where M_w and M_y are the masses (kg) of water and dry matter of yam tuber, C_{pw} and C_{py} are the specific heat capacity of water and yam in J/kgK respectively while T_{amb} and T_{st} are ambient and storage temperatures (K) correspondingly. Moisture content of yam tuber is 65% (wet basis) (Njie et al., 1998) while its specific heat capacity is 2.152 kJ/kgK (Oke et al., 2008).

At this storage temperature, yam is dormant, and sprouting is avoided. Hence, respiratory rate of yam cells is 3ml CO_2/kg/h (Diop, 1998). According to Peiris et al., (1997), the relationship between CO_2 produced during respiration and heat released is

$$Q_{hres} = M_{CO_2} x\ 1.08485\ x 10^{-2} \tag{5.18}$$

Where Q_{hres} represents respiratory heat in J/kg/hr, $M_{CO_2}$is the mass of CO_2 released in g/kg/h. Therefore, Q_{res}

$$Q_{res} = \frac{Q_h}{3.6} \qquad [kW/kg] \tag{5.19}$$

Where Q_{res} is respiratory heat generation in kW/kg of yam which is estimated to be 1.77x 10^{-5} kW/kg of yam.

Heat losses within the cold room are conduction, convection and radiation. The cold storage is insulated with of corkboard which is placed between inner pinewood and outer concrete blocks. Air gap between these materials is almost unavoidable. Hence, heat loss by convection is considered negligible. The total area in contact with air is 109 m^2. The thermal conductivities of pinewood, corkboard and concrete are 0.151 $Wm^{-1}K^{-1}$, 0.0433 $Wm^{-1}K^{-1}$ and 0.762 $Wm^{-1}K^{-1}$ respectively. Therefore, heat loss per square meter through the wall of the cold storage can be defined as in equation 5.20 (Tiwari et al., 2016)

$$Q_{l-unit} = \frac{R_T}{T_{st} - T_{amb}} * \frac{1}{1000} \tag{5.20}$$

Where Q_{l-unit} is the heat loss per unit meter through insulation in kW/m; R_T is the total heat resistance of materials in W/K while T_{st} and T_{amb} represent storage and ambient temperatures in K respectively. The conversion factor from W to kW is 1000.

$$R_T = \frac{1}{A}\left(\frac{S_p}{K_p} + \frac{S_{cb}}{K_{cb}} + \frac{S_{ct}}{K_{ct}}\right) \tag{5.21}$$

Where S_p, S_{cb} and S_c represent thickness of pinewood, corkboard and concrete respectively while K_p, K_{cb} and K_{ct} are the thermal conductivities of pinewood, corkboard and concrete respectively.

Heat loss by radiation is calculated from equation 5.22.

$$Q_{Rad} = \in * \sigma * (T_s^4 - T_a^4) * \frac{A}{1000} \tag{5.22}$$

Where:

$\in$	Emissivity coefficient of the material	[-]
σ	The Stefan-Boltzmann Constant	[W/m^2 ^{0}K^4]
T_s	Absolute temperature of the hot body	[^{0}K]
T_a	Absolute temperature of the cold surroundings	[^{0}K]
A	Area of the cold store in contact with cold air	[m^2]

The emissivity used was 0.94 for rough concrete, the Stefan-Boltzmann constant is a constant ($5.67*10^{-8}$) and the area (A) in contact with the cold side is 79 m^2.

5.2 Modelling methodology

In this section, details of the simulation method and validation of the AD processes together with the CCHP are presented. The results of the parametric studies are also presented and discussed. In addition to the thermodynamic properties of the streams that have to be defined in AP, the user is also obliged to specify the components of the input streams. This would enable AP to calculate the output of the stream. Hence, for the AD processes and drying unit, the composition of the biomass was first determined. For the AD system, the required compositions of the biomass that need to be determined are moisture content, total solids, volatile solids and ash content. The carbohydrate, protein and lipids component of the biomass are defined as the percentage of volatile solid component. In this, the considered biomass for the AD are cattle market waste and agricultural residues while cassava cake is considered for the drying system. Hence, the methodological approaches adopted are: evaluation of biomass availability; biomass characterisation, component analysis and simulation.

5.2.1 Evaluation of biomass availability- cattle market waste

The study area as described earlier is a market community where agricultural products are sold every 5th day and lots of market waste mainly cattle dung with leftover grasses is generated particularly at the cattle market which is situated on about 5 acres of land. At the moment, there is no data on the waste generation from the market. So, the first approach was to evaluate the actual size of the land occupied by cattle section of the market and determine the number of cattle in the market. This would help to evaluate the amount of waste being generated.

5.2.1.1 Determination of cattle market size and numbers of cattle in the market

A nearby village is currently being used as the research village for an ongoing cassava research project-CAVA II which is a Bill Gates foundation sponsored project and being implemented by the International Institute of Tropical Agriculture, Ibadan and the Federal University of Agriculture Abeokuta. So, five research students from CAVA II project volunteered for the sampling. The volunteers were first briefed on the objectives of the survey and the brief was followed with training during which questions on the survey were taken one after the other. The actual sampling and data collection were done between 7th and 15th December 2015. Quadrat sampling which is an ecological sampling technique usually used to determine the number of species per unit area of land (Krebs, 2014) was used to obtain the number of cattle per unit area. Three quadrats of size 18.23 x 36.58m^2 were measured using wooding pegs and measuring tape (BMI EA53, China). On market days, loading and offloading of cows is continuous throughout the day. Hence, counting of cows in each quadrat were repeated every 1 hour from 8 am to 4 pm in the evening. This were done on two market days consecutively and the average cow per quadrat is noted.

5.2.1.2 Sampling collection and preparation

Samples were collected from different parts of the cattle market dumping ground. Fresh samples from the cleaning done on the days of data collection were equally collected. Samples are collected on cleaned dried plastic bottles, kept in a plastic cooler during transit and stored at 4˚C. The sample bottles were placed in plastic container and ice cubes were used to maintain its temperature during transit from Nigeria to Newcastle and it was also kept in laboratory at 4˚C until analysis.

5.2.1.3 Determination of daily waste

Cleaning is done weekly, thus, because of complexity in cleaning, two quadrats of size 18.23 x 36.58m^2 were randomly selected which was measured using wooding pegs and measuring tape (Model: BMI EA53, China). The selected quadrats were cleaned, and the generated waste was measured using weighing balance (Model: Hana, China) shown in the. Figure 5-8

Figure 5-8: Weighing balance

5.2.1.4 Waste Characterisation

As in the waste quantification, it will be challenging to sort all the waste. So, as quantification was on-going, every 15th head-pan was sorted, and the quantities of plastic bags, plastic bottles, paper, woods, textiles and other foreign materials were determined using weighing balance.

5.2.2 Determination of the proximate composition of the waste

The compositions of the waste determined are moisture content, total solids, volatile solids, ash content, total crude protein, crude fat and carbohydrates. The insoluble part of carbohydrate such as cellulose, hemicellulose and lignin are further analysed while the remaining components is assumed to be glucose. However, while market waste was analysed for its compositions; that of farm residues are sourced from empirical studies. This is because, market waste is heterogeneous, and no previous work had been reported on its composition while farm residues of interest: maize, cassava, tomato and cashew apple residues are homogeneous and have widely been researched. Analysis was done using American Public Health Association's (APHA) methods for water and waste analysis (American Public Health Association, 2005).

5.2.2.1 Moisture content determination (APHA 2540-B)

This was determined using American Public Health Association (APHA 2540-B) standard as discuss below: Empty porcelain crucible was washed and dried for 1 hour at 104^{0}C in oven (Morgan Grundy-50L, UK). The crucible was then cooled in the desiccator and weighed with analytical balance (Mettler AJ 150, Switzerland). Waste sample was put into the crucible and weight of sample with crucible was noted. The crucible with sample was placed in the oven at 105^{0}C for 1 hour. It was then removed, cooled, weighed. The process of heating, cooling and weighing was continued until constant weight was obtained and the final weight was noted. The experiment was conducted in triplicate for each sample. The moisture content was calculated as in equation 5.23:

$$\text{MC}=\left(\frac{(W1-W)-(W2-W)}{(W1-W)}\right)*100 \qquad (5.23)$$

Where MC, W, W1 and W2 are moisture content (%), weight of empty crucible (g), weight of sample (g) before and after drying respectively.

5.2.2.2 Determination of Volatile Matter (APHA 2540-E)

This was determined using American Public Health Association (APHA 2540-E) standard as enumerated below. Empty porcelain crucible was washed and ignited for 1 hour at 550^0C in muffle furnace (Morgan Grundy-N10604-50, UK). The crucible was then cooled in the desiccator and weighed with analytical balance (Mettler AJ 150, Switzerland). Waste sample was put into the crucible and weight of sample with crucible was noted. The crucible with sample was placed in the oven at 104^0C for 24hrs. It was then removed, cooled, weighed and the final weight was also noted. The crucibles were then transferred to a cleaned, cooled muffle finance and ignited for 1 hour. The crucibles were then removed, cooled and weighed. Ignition was repeated for 30 minutes, followed by cooling, desiccating and weighing steps until weigh difference between is less than 4%. The experiment was also done in triplicate for each sample.

Total solids and volatile solids were calculated from equations 5.23 and 5.24 respectively.

$$\%\ \text{Volatile matter} = \left(\frac{(A-C)}{(A-B)}\right)*100 \qquad (5.24)$$

Where

A = Weight (g) of dried residue with dish,

B= Weight (g) of dish,

C= Weight (g) of residue + dish after ignition.

C= Weight (g) of residue + dish after ignition.

5.2.2.3 Ash content (APHA 2540-E)

Ash content of the sample was evaluated as the residue from section 5.2.2.2 above and it was evaluated using equation 5.25

$$\%\text{Ash} = \left(\frac{(C-B)}{(A-B)}\right) * 100 \qquad (5.25)$$

Where A, B and C are as defined above.

5.2.2.4 Fixed Carbon

Fixed carbon is determined by difference as presented by:

$$\%\ \text{Fixed carbon} = 100 - (\%Moisture + \%Volatile + \%\ Ash) \qquad (5.26)$$

5.2.2.4 Protein analysis (APHA -4500-N_{org})

Kjeldahl method is employed in determining the crude protein content of the sample. It was determined using American Public Health Association (APHA 4500-N_{org}) standard as enumerated below: The method involves breakdown of sample's protein with sulphuric acid to nitrogen in the form of ammonium sulphate. The breakdown is represented in equation 5.27

$$C_nH_mN_x + H_2SO_4 \rightarrow nCO_2 + \frac{1}{2}mH_2O + \frac{1}{2}x(NH_4)_2SO_4 \qquad (5.27)$$

Where $C_nH_mN_x$ represents the biomass. The solution is subsequently heated for the digestion of the sample. Caustic soda is then added to release ammonia from the complex ammonium sulphate salt formed as shown in the equation 5.28

$$(NH_4)_2SO_4(aq) + 2NaOH \rightarrow Na_2SO_4(aq) + 2H_2O(l) + 2NH_3(g) \qquad (5.28)$$

The released ammonia is separated by distillation and captured into boric acid as shown in the equation 5.29

$$B(OH)^3 + H_2O + NH_3 \rightarrow NH_4 + \ B(OH)^{4-} \qquad (5.29)$$

This is then followed with back titration with hydrochloric acid to quantify the ammonia. The Kjedhal apparatus used is Kjeldatherm KT8S (Gerhardt, UK) as indicated in the Figure 5-9 and comprises of digestion, distillation and titration units. Details of the steps used is presented below:

About 10 g of sample is accurately weight into the digestion tube. Two tablets of KJELCUT CU^{TM} which server as catalyst is added. About 28 ml of 5N concentrated sulphuric acid is then added, the tube is placed in the digester rag and digested at 373˚C for 2 hours. 100 ml of distilled water is added to dilute the solution and prevent strong reaction in the subsequent step. The solution is then titrated against 0.1mol/L of dilute hydrochloric acid using 2 drops of methyl orange as indicator. Blank titration is done without the sample.

Figure 5-9: The Kjeldahl apparatus

The nitrogen and crude protein content are evaluated using equations 5.30 and 5.31 respectively

$$\%N = \frac{1.4007 * C * (W - Wo)}{E} \qquad (5.30)$$

Where N, C, E, W and W_0 are nitrogen, hydrochloric acid concentration, weight of the sample, consumption standard solution sample and consumption standard solution blank.

$$\%Crude\ protein = \%N * PF \qquad (5.31)$$

Where PF is the conversion factor and 4.31 is assumed in this study since this has been proved to be suitable for animal manure (Chen et al., 2017).

5.2.2.3 Raw fat analysis (APHA- 5520 D)

Analysis of raw fat is conducted with Soxhlet apparatus which has three units: percolator (heating and refluxing), thimble (sample holding) and siphon (emptying system). The principle involves heating of solvent, in this case hexane, by refluxing. The vapour is subsequently distillated and then travel back into the thimble where the hot distillate leaches away the non-volatile components of the sample. The thimble got filled up and siphoned into the percolating unit where the cycle starts again.

Glass apparatus are rinsed with petroleum ether, dried in the oven at 102^0C. It is then cooled in the desiccator. About 5 g of grounded and dried sample is accurately weight into the thimble. The thimble is then placed into the Soxhlet extractor (Figure 5-10). The round bottom flask of the extractor is then filled with 200ml of hexane. The whole mantle is placed on heating as shown in the figure and left for 16 hours. The system is then dismantled, and solvent recovered. The sample is then dried in the oven; cooled in the descicator and weighed.

Figure 5-10: Soxhlet extractor.

The percentage crude fat is evaluated with equation 5.32

$$\%Crude\ fat = \frac{W_2 - W_1}{W} x\ 100 \qquad (5.32)$$

Where W_2, W_1 and W represent weight of defatted sample with thimble, weight of thimble and weight of the sample respectively. The experiment is performed in triplicate and the average was noted.

5.2.2.4 Carbohydrate analysis

The percentage carbohydrate is estimated as the total carbohydrate by difference method using equation 5.33

$$Total\ Carbohydrate = 100 - [weight\ in\ grams\ (protein + fat + water + ash)\ in\ 100g\ of\ food] \qquad (5.33)$$

5.2.2.5 Determination of lignocellulose content

Cellulose, hemicellulose and lignin are the insoluble lignocellulose content of biomass. Gravimetric, chromatography and spectroscopic are the commonly used methods of analysis in the literature (Huang et al., 2011; Demirbaş, 2005; Lin et al., 2010). However, gravimetric method appears to be simple, cost effective and compares favourably with other methods (Ayeni et al., 2015). Hence, the lignocellulose content of the sample was analysed following the method adopted by Ayeni et al., (2015) and Sluiter et al., (2012). The method involves extraction and two staged hydrolysis of the biomass.

2.5 g of dried sample was measured into cellulose thimble. The process of Soxhlet extraction detailed in the section 5.2.2.3 was repeated but with acetone as the solvent. The extracted sample was then placed in the desiccator for cooling before dried to constant weight in the oven at 105^0C. The different in weight between the original sample and extracted sample was noted as the weight of the extractives. 1 g of extracted sample was weighed into a conical flask and 150 mL of 0.5 mol/L NaOH was added. The mixture was boiled for 3.5 hrs with distilled water. This was followed by Vacuum filtration and washing until a neutral PH is achieved. The treated sample is then dried to an invariable weight at 105^0C in an oven. Hemicellulose is evaluated as the difference between treated and untreated sample. Thereafter, 3 mL of 72% H_2SO_4 was added to 300 mg of extractive-free sample in a crucible. It was placed in the water bath at 30^0C for 2 hours and thoroughly stirred every 10 minutes to enhance hydrolysis. About 84 mL of distilled water was then added before the sampled was autoclaved at 121^0C for 1 hr. Vacuum filtration was done to filter the hydrolysates. It was then dried at 105^0C to evaluate the acid insoluble lignin. However, the ash content was accounted for by ashing the hydrolysates in muffle furnace at 575^0C. Acid insoluble lignin is calculated as the difference between dried hydrolysates and ash content. The absorbance of hydrolysed sample was evaluated at 320 nm and this was used to determine the amount of acid soluble lignin. The percentage lignin in the extracts free sample was evaluated using equation 6.12 (Sluiter et al., 2012).

$$\%\ Lignin_{extract\ free} = \%\ acid\ soluble\ Lignin + \%\ acid\ insoluble\ Lignin \qquad (5.34)$$

Hence, lignin on as received basis is calculated using equation 5.35

$$\%\ Lignin_{as\ recieved} = \%\ Lignin_{extract\ free} + \frac{100-\%\ extractives}{100} \qquad (5.35)$$

5.2.3 Ultimate analysis of the waste (BS 1016-104)

This was evaluated using the British Standard (BS 1016-104). The elemental compositions of the waste were determined with elemental analyser Model 1108 (Carlo-Erba, Milan, Italy) shown in the Figure 3.5. However, due to the microscopic nature of the quantity required, the sample had to be specially prepared before sample analysis.

5.2.3.1 Sample preparation for elemental analyser

Samples are dried as described in section 5.2.2.2. It is then cooled and stored in the desiccator. The cooled samples were then grounded with blender, MJ-40BM03B (Cookworks, UK), sieved with 0.5micron stainless steel mesh and stored in covered samples bottles for analysis. The elemental analysis of the sample was conducted at the School of Chemistry, Northem Carbon Research Laboratories, Department of Chemistry, Bedson Building, Newcastle University.

5.2.3.2 Elemental analysis

About 1 mg of the sample was measured with ultra-micro balance, shown in Figure 5.11 Model Cubis® 4504MP8 (Sartorius, UK) into the tin capsule. The capsule is then placed inside the auto-sampler of the elemental analyzer, Model 1108 (Carlo-Erba, Milan, Italy), Figure 5-12 which is equipped with PC based software: Eager 200 for Windows™ for quantification of the elemental Carbon, Hydrogen, Nitrogen and Sulphur contents of the sample. The machine uses Dumas method which involves flash combustion of samples at high temperature and the resultant gases are analyzed. The auto-sampler is purged with helium and as auto-sampler rotates samples are released into the combustion reactor which is being kept at 900C. As sample is being released, oxygen is simultaneously injected into the chamber and the tin capsule undergoes flash combustion. The reactor also contains copper

(II) oxide and platinised alumina which act as catalysts to ensure complete oxidation of combustion gases. Helium gas acts as carrier gas to take the combustion products through reactor and in the present of oxygen and catalysts, all carbon is oxidised to CO_2, Nitrogen to nitrogen oxide and hydrogen to water. The resulting gas mixtures is then carried through gas chromatography where it is separated and detected by a thermal conductivity detector (Eager 200 for Windows^{TM}), which produces an output signal relative to the concentration of individual gases in the mixture.

Figure 5-11: Ultra-micro balance

Figure 5-12: Carlo-Erba elemental analyzer.

5.2.4 Determination of theoretical biogas potential of the waste

Having determined the elemental composition of the waste, the theoretical methane composition (Shen et al., 2015) was evaluated using Buswell's equation (Equation 6.14 and 6.15). This is done for two reasons: 1) the theoretical biogas generation potentials of the biomass can be compared with the values predicted by AP software; 2) the extent of the deviation can be used do judge the correctness of elemental analysis. Buswell equation is suitable for predicting the methane generation potential of a sample of known elemental compositions (Hidalgo and Martín-Marroquín, 2015). The shortcoming of the method is that it assumes a complete degradation of the organic components of the waste which is not possible in real case particularly due to difficulty in degradation of lignocellulosic materials (Mussoline et al., 2013). Thus, provision must be made for the extent of biochemical conversion of a sample using data from the experimental digestion of similar sample. In this case a 70% degradation is assumed.

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \qquad (5.36)$$

$$B_u(\frac{l}{kgVS} = \frac{\left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right) x\ 22.4}{(12a + b + 16c)} \qquad (5.37)$$

Where a, b, c, d and e symbolize the fractions of carbon, hydrogen, oxygen, nitrogen and sulphur in the biomass composition while B_u is the methane potential in l/kgVS.

After determination of biogas composition with Buswell equation, the theoretical methane production is evaluated using the biomass carbon content.

5.2.5 Evaluation of biomass availability-crop residue

As noted in Chapter 3, the studied village is purely agrarian with 2.7 ha of land being cultivated per household. The predominantly cultivated crops are cassava, maize, tomato and cashew with 100%, 92%, 90% and 54% of farmers respectively currently cultivating the crops. Therefore, to quantify the available crop residue, residue to product ratio has been widely used in the literature (Simonyan and Fasina, 2013; Helwig et al., 2002) and it is adopted in this study using equations 6.16 (Garba and Zangina, 2015).

$$RS_{prod} = PR_{prod} \text{ x } SGR\ X\ S_{avl} \qquad (5.38)$$

Where RS_{prod} is residue (straw, husk, leaves) production in kg/yr., PR is the households' crop production (kg/yr.), SGR is the residue grain ratio while $S_{avl}$is the percentage of the residue available for energy recovery. Hence, the calculated yields and proximate compositions of various different crops residues as obtained from various literature are presented in the Table 5-4 and Table 5-5respectively:

Table 5-4: Crop residue

	Maize	Cassava	Tomato	Cashew
Yield (kg/ha)	1,850	7,720	3,956	2,286
Planted/household (ha/yr.)	2.154	1.579	1.538	0.486
Household production (kg/yr.)	3,985	12,190	6084	1111

Residue type	Stalk	Cob	Husk	Tops	Peeling	Stem	Cashew apple
Moisture content	15	7.53	11.11	70-80	15	45	20.3
Residue grain ratio	2.0	0.273	0.20	0.25	0.3	0.35	10.85
Residue availability (%)	70	100	60	83.5	50	100	90
Residue/household (Kg/yr.)	5,579	1088	478.2	2544.9	1,828.5	2,129.4	10,849
Total residue/ household/yr.	**24,497**						

Table 5-5: Proximate composition of the crop residues

	Maize			**Cassava**		**Tomato**	**Cashew**
	Stalk	Cob	Husk	Tops	Peeling	Stem &leaves	Cashew apple
References	(Simonyan and Fasina, 2013)	(Simonyan and Fasina, 2013)	(Simonyan and Fasina, 2013)(Helwig et al., 2002)	(Okudoh et al., 2014)	(Ohimain et al., 2013; Serpagli et al., 2010)	(Díaz de León-Sánchez et al., 2009) (Silva et al., 2016)	(Sivagurunathan et al., 2010; Talasila and Shaik, 2015) (Oni et al., 2011)
Volatile matter (wt.% db)	72.9	77.0	72.2	77.6	68.5	88.6	79.8
Fixed carbon (wt. % db)	15.1	17.2	22.0	13.9	22.6	7.8	18.7
Ash (wt. % db)	12.0	2.9	2.9	8.5	4.4	3.6	1.5
Carbohydrate (wt. % db)	83.7	75.9	75.9	64.0	62.4	61.4	80.7
Raw protein (wt. % db)	2.8	10.1	10.1	22.0	8.6	20.9	13.0
Raw fat (wt. %)	1.5	11.1	11.1	5.5	24.6	14.1	4.8

5.3 Aspen Plus simulation of the model

Details of the rational for the choice and principles of Aspen Plus software had been discussed in the literature review. Here, details of its application to the simulation of AD process as well as tri-generation system such as the ICE; absorption chiller and convective dryer is discussed.

5.3.1 Simulation of AD process

Simulation of AD process was performed following the earlier studies reported by Peris (Peris, 2011) and Rajendran et al (Rajendran et al., 2014) which were both based on ADM1 (Anaerobic digestion model 1) (D. J. J. Batstone et al., 2002). Substrates are thought to mainly compose of carbohydrate, protein, fat and water. The model broke down AD process into hydrolysis, acidogenesis, acetogenesis and methanogenesis which are represented with kinetic equations which takes into account the effect of pH inhibition. The kinetic equation used in the model is presented in the Appendix 3.

Table 5-6: Reaction equations for the hydrolysis step (Rajendran et al., 2014)

No	Compound	Hydrolysis Reaction
1	Starch	$(C_6H_{12}O_6)n + H_2O \rightarrow nC_6H_{12}O_6$
2	Cellulose	$(C_6H_{12}O_6)n + H_2O \rightarrow nC_6H_{12}O_6$
3	Hemicellulose	$(C_5H_8O_4) + H_2O \rightarrow 2.5C_2H_4O_2$
4	Hemicellulose	$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$
5	Xylose	$C_5H_{10}O_5 \rightarrow C_5H_4O_2 + 3H_2O$
6	Cellulose	$C_6H_{12}O_6 + H_2O \rightarrow 2C_2H_6O + 2CO_2$
7	Ethanol	$2C_2H_6O + CO_2 \rightarrow 2C_{52}H_6O_2 + CH_4$
8	Soluble protein	$C_{13}H_{25}O_7N_3S + 6H_2O \rightarrow 6.5CH_4 + 6.5CO_2 + 3H_3N + H_2S$
9	Triolein	$C_{57}H_{104}O_6 + 3H_2O \rightarrow C_3H_8O_3 + 3C_{18}H_{34}O_2$
10	Tripalmate	$C_{51}H_{98}O_6 + 8.436H_2O \rightarrow 4C_3H_8O_3 + 2.43C_{16}H_{34}O$

11	Palmito-olein	$C_{37}H_{70}O_5 + 4.1H_2O \rightarrow 2.1C_3H_8O_3 + 0.9C_{16}H_{34}O + 0.9C_{18}H_{34}O_2$
12	Palmito-linolein	$C_{37}H_{68}O_5 + 4.3H_2O \rightarrow 2.2C_3H_8O_3 + 0.9C_{16}H_{34}O + 0.9C_{18}H_{34}O_2$
13	Insoluble protein	$Keratin + 0.334H_2O \rightarrow 0.045C_6H_{14}N_4 + 0.048C_4H_7NO_2 + 0.047C_4H_9NO_3 + 0.172C_3H_7NO_3 + 0.074C_5H_9NO_2 + 0.25C_2H_5NO_2 + 0.047C_3H_7NO_2 + 0.067C_3H_6NO_2S + 0.074C_5H_{11}NO_2 + 0.046C_6H_{13}NO_2 + 0.0036C_9H_{11}NO_2$

Hydrolysis is extracellular while the remaining stages of AD process are intracellular. Thus, different conditions are required for optimization. Therefore, two sets of reactors are used for the process. The first reactor which was modelled with 13 equations (Table 5-6) is for hydrolysis step. It uses the stoichiometric reactor (Rstoic) of Aspen Plus where biomass flow rates, biomass composition, temperature, pressure, and fractional conversion were defined. Feed substrate was defined in the following way:

Water: There must be enough water to enhance optimum performance of microorganisms. However, total solid of 5-15 has been found to be the range at which microbial activities is the best (Zhang et al., 2013; de Mes et al., 2003). Hence, feedstock was defined as 10% total solid and 90% water.

Carbohydrates: Carbohydrates in models are found as soluble, insoluble and inert. In this model, soluble carbohydrate is designated as dextrose while cellulose and hemicellulose represent insoluble carbohydrate. Inert carbohydrate is lumped with the substrate’s ash content which is model as inert. During hydrolysis, insoluble carbohydrate are extracellularly converted to soluble carbohydrates (Angelidaki et al., 1993) as shown in the equation 5.39

$$(C_6H_{10}O_5)_{is} = Y_c(C_6H_{10}O_5)_s + (1 - Y_c)(C_6H_{10}O_5)_{in} \tag{5.39}$$

Where Y_c is the degree of degradability of the biomass; $(C_6H_{10}O_5)_{is}$ symbolysis the original biomass substrate and $(1 - Y_c)$ is the undegradable fraction of the biomass. Thus, this is implimented as the fractional conversion in the Rstioch reactor.

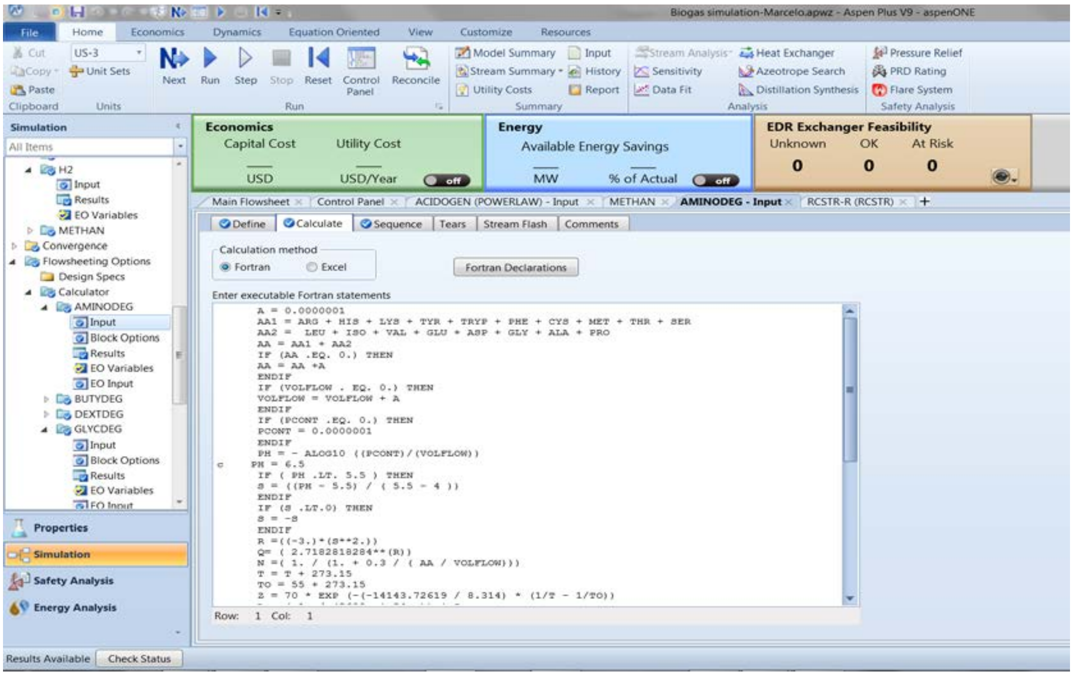
Protein: Gelatin is assumed as a model protein since it is representative of an average amino acid composition. It is model as soluble and insoluble protein which follows the similar patern as in equation5.39. Insoluble protein is represented as keratin and both are simulated as pseudocomponent in Aspen Plus. To define these components, properties such as heat of formation, heat of volarisation, Gibbs energy, critical temperature and pressure etc were provided.

Lipids: Lipid is modelled as glycerol trioleate which is broken into triolein, tripalmitin and palmitoleic acid.

The second reactor is where acidogenesis, acetogenesis and methanogenesis stages of AD processes take place. It is modelled with the continous stirred tank reactor (RCSTR) of Aspen Plus. Here, the biochemical reactions, kinetic constants and activation energies of each of the 33 reactions involved are supplied. Besides, the rate of reactions and pH inhibition functions for the aformentioned three stages of the digestion are provided using built in FORTRAN language of Aspen Plus. These stages of digestion are also influenced by the temperature, solid retention time and hydraulic retention time (Kaparaju et al., 2007; Hagos et al., 2017). Hence, temperature and residence time are designed inputs. Example of calculator block used for the amino acid degeneration is shown in the. Figure 5-13.

Non-Random Two-Liquid model (NRTL) was selected as the property method as it compares and estimates the mole fractions and activity coefficients of individual compounds (Peris, 2011; Rajendran et al., 2014), while also enables the liquid and the gas phase in the biogas production. The Aspen Plus model of the AD is illustrated in Figure 5-14.

Modelling is done at thermophilic (55^0C) and mesophilic (35^0C) conditions. Similar chemical reactions, activation energy and kinetic equations are adopted for the two processes. It is worth to note that activation energy is a temperature dependent variable and expected to differ between the two operating conditions. However, as in ADM1, it is assumed constant for the operating temperature between 0^0C and 60^0C (D. J. J. Batstone et al., 2002). Nevertheless, the kinetic constants are different between the two processes. The kinetic constants for the thermophilic process are largely taken from ADM 1 while that of mesophilic are sought from different published empirical studies. More so, a conservative 20 to 30% reduction in the fractional conversion is assumed for the hydrolysis stage in the first mesophilic reactor.



Calculation method: ● Fortran ○ Excel

Enter executable Fortran statements

```
      A = 0.0000001
      AA1 = ARG + HIS + LYS + TYR + TRYP + PHE + CYS + MET + THR + SER
      AA2 =  LEU + ISO + VAL + GLU + ASP + GLY + ALA + PRO
      AA = AA1 + AA2
      IF (AA .EQ. 0.) THEN
      AA = AA +A
      ENDIF
      IF (VOLFLOW . EQ. 0.) THEN
      VOLFLOW = VOLFLOW + A
      ENDIF
      IF (PCONT .EQ. 0.) THEN
      PCONT = 0.0000001
      ENDIF
      PH = - ALOG10 ((PCONT)/(VOLFLOW))
c    PH = 6.5
      IF ( PH .LT. 5.5 ) THEN
      S = ((PH - 5.5) / ( 5.5 - 4 ))
      ENDIF
      IF (S .LT.0) THEN
      S = -S
      ENDIF
      R =((-3.)*(S**2.))
      Q= ( 2.7182818284**(R))
      N =( 1. / (1. + 0.3 / ( AA / VOLFLOW)))
      T = T + 273.15
      TO = 55 + 273.15
      Z = 70 * EXP (-(-14143.72619 / 8.314) * (1/T - 1/TO))
```

Row: 1 Col: 1

Figure 5-13: FORTRAN language for amino acid degradation

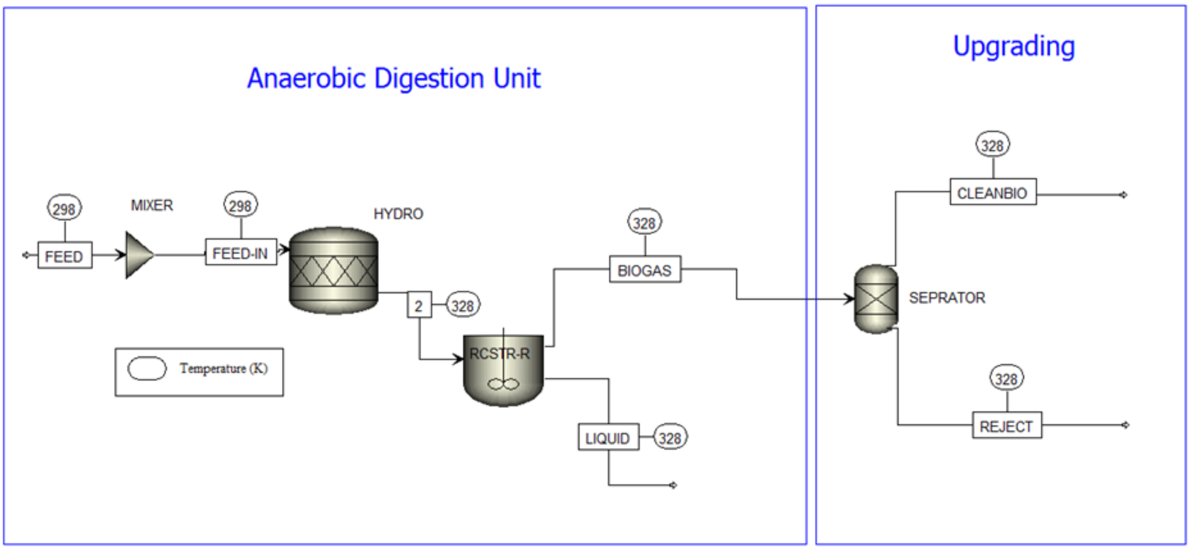


Figure 5-14: Aspen Plus model of the AD process.

5.3.1.1.Verification and Validation of AD process simulation

Model verification which is a process that shows whether a model is rightly built (Sokolowski and Banks, 2009) was done using data from experimental anaerobic digestion studies from the Swan Centre for Energy research, Newcastle University and literature sources. To accomplish this, output data from the AD model was measured against what was expected from the input data. ADM1 integrates kinetic data for specific purposes and coefficient values are equally provided. These need to be altered depending the process approach and feedstock materials. This is accomplished by: sensitivity analysis of the most suitable parameters to each controlled processes and modification of the coefficients based on literature values.

The model is validated against three experimental case studies:

I. Brewery spent grain was used as substrate. The substrate is characterized having 25%; 96%; 6.6%; 27.13%; 62.27% total solid, volatile solid, crude fat, crude protein and carbohydrate respectively. The experiment was performed both at mesophilic (35C) and thermophilic (55C) conditions with the reactor volume, organic loading rate and hydraulic retention time of 5L; 5gVSday^{-1} and 25 days respectively (Siqueiros-Valentia (Siqueiros, 2017)). However, characterization of its carbohydrate content such as cellulose, hemicellulose and lignin were as reported by Muthusamy (Muthusamy, 2014) and Senthilkumar et al (Senthilkumar et al., 2010) as these were not reported by the author.

II. The substrate for the second case study is cow manure which is characterize with 6% total solids and 80% volatile solid. The organic loading rate, hydraulic retention time and reactor volume are 0.33 L/day; 15 days and 5 L respectively Kaparaju et al., (2009)). Compositions such as cellulose, hemicellulose, lignin, ash content, lipid, protein and carbohydrate are 25.97%, 35.57%, hemicellulose 14.94, 20.06, 1.51, protein and carbohydrate 70.15 respectively (Budiyono et al., 2011).

III. The third case used for the validation is sugar beet pulp having total solids; volatile solid; hemicellulose, cellulose, lignin; and protein of 24.2%; 93.4%; 70.2 g kg^{-1} wet weight; 32.2 g kg^{-1} ; 20.8 g kg^{-1} and 21.8 g kg^{-1} respectively. The digestion was performed at thermophilic temperature (55± 0.5^{0}C) with a 4 L continuous stirred reactor, using 4 gVSl^{-1}day^{-1} organic loading rate and 68.5 hydraulic retention time (Suhartini et al., 2014).

5.3.1.2 Parametric studies of the AD system

As stated earlier, some of the factors that do affect AD process are temperature, PH and the organic loading rate. These factors are varied to study their effects on the AD process.

Temperature: The experimentally evaluated activation energies and kinetic constants are available for both thermophilic and mesophilic systems. So, the operating temperature checked for the mesophilic are 25, 30, 35, and 40C while 50 to 65 was evaluated for the thermophilic process.

pH: The pH of the system was also checked between 5.5 to 6.5 and its effects on the biogas production examined while other parameters are kept constant.

Organic loading rate: The OLR was is varied ±20% to observe its effects on the biogas production.

5.3.2 Simulation of internal combustion engine

A reciprocating internal combustion engine is chosen for the system due to its tendency to withstand partial loading. The technology is matured and in the case of Nigeria, local mechanics are readily available for routine maintenance since it has similar features with gasoline or diesel fired engine that is predominantly being used for both households and commercial self-generated electricity. It also works perfectly in the extreme weather conditions of the tropic countries like Nigeria. Importantly, it is designed to work with low grade biogas which reduces cost and complexity of biogas purification. Thus, two turbocharged biogas powered Caterpillar engines G3306 and G3406 with 72 kWe and 103 kWe respectively were considered (Caterpillar Inc., 2011). The specifications are indicated in the Table 5.7.

Table 5-7: Technical data of CAT G3306 and G3406

Particulars	**Unit**	**Quantity**	
Power	kW	72	103
Fuel consumption	Nm^3/h	42.2	57.6
Ambient air temperature	C	25	25
Jacket water temperature	C	99	99
Compression ratio		10.5:1	10.3:1
Combustion air flow rate	m^3/h	292	384
Displacement	L	10.5	14.6
Exhaust stack temperature	C	581	578
Exhaust gas flow rate	$^{M3}/h$	324	426
Heat rejection to jacket water	kW	99	123
Heat rejection to lubricant oil	KW	16	19

The theoretic configuration of the gas engine model was developed by (Abedin et al., 2013) and (Ajav et al., 2000). In their studies, the internal combustion engine is regarded as a thermodynamic open system or control system such that mass and energy inflow and outflow can be visualised. With this assumption, the model of the gas engine was developed in Aspen Plus software. To do this, gas engine is broken down into unit operations which includes compression, mixing, cooling, combustion and expansion which are subsequently model with the compressor, mixer, cooler, combustion reactor, expander units of Aspen Plus.

Peng-Robinson (PR) property package is employed. This is because PR fluid package is able to predict the thermodynamic behaviours of the participating fluids at the temperature and pressure range being used in this study (Aspentech Inc, 2013; Ekwonu et al., 2013; Damartzis et al., 2012). It is therefore seen as best fit since it has a vigorous database and equations capable of producing better predictions of equilibrium of hydrocarbons at high temperature and pressure.

Turbocharger: The engine has two turbochargers. Therefor a splitter is used to split the combustion air into two before entering the turbochargers which are modelled with compressor and cooler of AP. Isentropic efficiency and discharge pressure are the two inputs to the compressor. These are taken as 85% and 2 bars (Ekwonu et al., 2013) respectively. Inputs to the coolers are discharge pressure from the compressor and temperature. Heat discharge to intercooler is a manufacturer’s given parameters. So, the temperature difference is adjusted to obtain the stated heat rejection.

Mixer: This is used to mix the two streams together before entering the main compressor.

Compressor: Isentropic efficiency of 80% and pressure ratio were the two designed inputs to the compressor. The pressure ratio is adjusted to reflect the manufacturer’s engine compression ratio of 10.5.

Reactor: The fuel was modelled as 67% methane and 33% carbon-dioxide. Only methane takes part in the combustion reaction as described in the equation 5.40

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \qquad 5.40$$

Therefore, since the reaction has stoichiometry and complete combustion of methane is intended, the stoichiometry reactor of AP is employed (Aspen Technology Inc., 2000). Its specification are fractional conversion of 1, pressure of 10.5 bar and combustion temperature of 1200^{0}C.

Expander: it is modelled with the expander of AP. Its inputs are isentropic efficiency 85% and discharge pressure of 1 bar. The complete AP model of the engine is presented in the Figure 5-15.

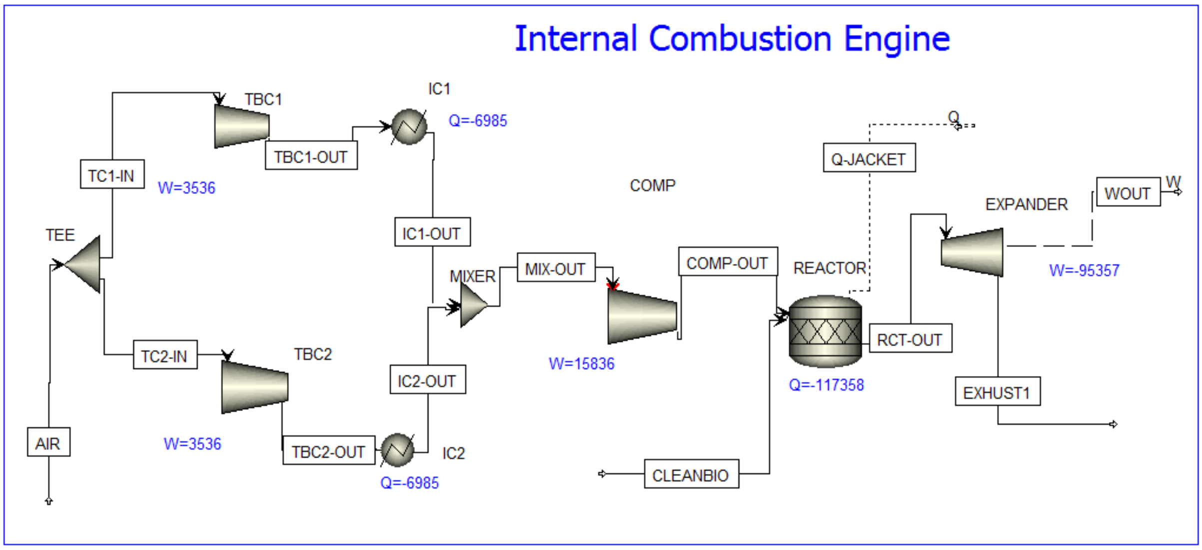


Figure 5-15: Aspen Plus model of gas engine

5.3.3 Modelling of absorption chiller

5.3.3.1: Description of chiller modelled

The chiller used in this study is a 5 tons water fired Yazaki WFC-SC5 absorption chiller. This chiller is chosen for the present work because of the following reasons:

- It is available in the commercial quantity and various small sizes.
- It is designed to work in the extreme weather conditions of the tropical countries at up to 50^{0}C ambient temperature (Yazaki Corporation Company, 2017).
- The chiller is to be used for the storage of agricultural products whose storage conditions varies between 5^{0}C to 15^{0}C. A one stage cycle with complex interconnectivity for internal heat recovery for pre-absorption (Yazaki Corporation Company, 2017).
- There exists literature on its simulation and experimental testing.

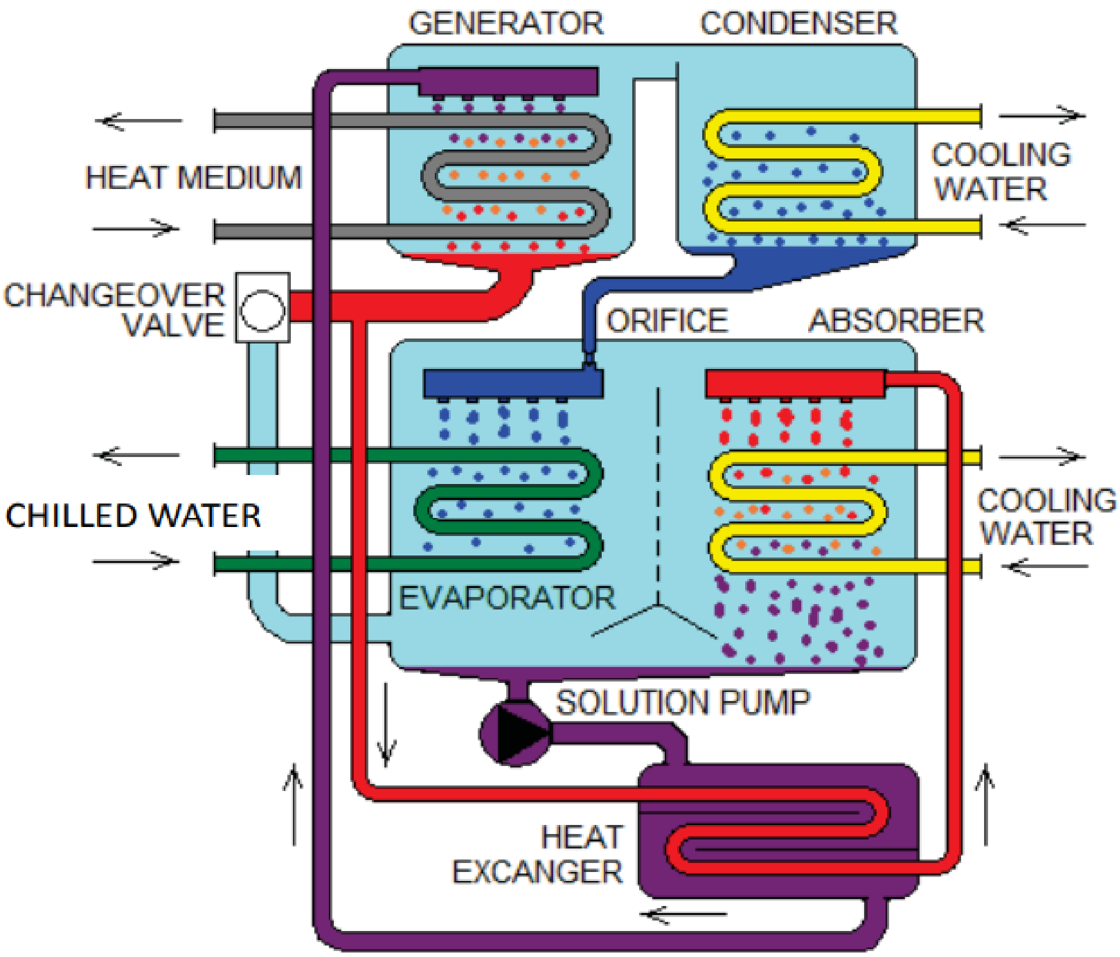


Figure 5-16: Internal flowsheet of Yazaki absorption chiller (Yazaki Corporation Company, 2017) .

Illustrated in the Figure 5-16 is the internal connectivity of the Yazaki absorption chiller. The lithium bromide/water mixture is heated in the generator by the heat energy supplied by gas burner or recovered heat. The refrigerant (water) vapour then flows to the condenser where it exchanges heat with the environment and becomes liquified. It is then passed through the expansion valve (orifice) where its pressure is reduced before going to the evaporator where it absorbs heat from chilled water and evaporates. More so, the weak solution coming from the absorber exchanges heat with strong solution coming from the generator where it is pre-heated before moving to the generator. The LiBr weak solution then moved to the absorber where it absorbs refrigerant and the heat of absorption is lost to the surrounding. The technical parameter of the modelled chiller is presented in the Table 5.8.

Table 5-8: Technical details of modelled chiller

Particulars	Specification

Cooling capacity (kW)	17.6
Evaporator pressure loss (kPa)	52.6
Maximum operating pressure (kPa)	558
Rated water flow (l/s)	0.77
Heat rejection (kW)	42.7
Cooling temperature	12.5 in/5 out
Cooling water	31 in/35 out
Absorber pressure loss (kPa)	38.3
Heat input	25.1
Operational temperature (C)	70-95
Generator pressure loss (kPa)	95.8
Electricity consumption (W)	48

5.3.3.2: State points and assumptions

Following the absorption cycle thermodynamic process described in section 2.3.2, Yazaki absorption chiller simulation is done using model developed by (Bonab et al., 2015) and (Somers et al., 2008) with some modifications to the heat exchanging systems. For convenience, the following standard will be used for state points and will be followed for the modelling of water/LiBr chiller. The absorber exit is state B. There is a break between the absorber exit and pump inlet (A). This is necessary to evaluate the convergence of the model. The pump exit is state 2, the solution heat exchanger exit heading towards the generator is 3, the liquid exit of the generator is 5. Exit of the solution heat exchanger moving to the solution valve is state 6 while the valve exit is 12. The vapour exit of the generator is state 7 while exit of the condenser is 8, the refrigerant valve (Valve 1) exit is 9 while exit of the evaporator is 10. The input heat to the generator is 13 while its exit is 14. The assumptions and state points use for the model is presented in Table 5.9. These state points are chosen because they are the frequently used points in absorption cycle simulations (Somers et al., 2008). The choice of these points will also make comparison and validation with published data easy.

Table 5-9: State points and assumption for the modelling

State (s)	Assumption
A	Saturated liquid
B	Determined by the absorber model
2	Dictated by the solution pump model
3	Controlled by solution heat exchanger
5,7	Controlled by the generator model
8	Vapour quality 0
9	Defined by the valve 1 model
10	Determined by the evaporator model
12	Defined by the solution valve 2

5.3.3.3: Component breakdown and modelling

State point A: Aspen-plus uses a consecutive solver. Thus, a break may be put in the model to give input for the system. This break is put in the state point A. Since the exit of the absorber (State point B) serves as inlet of the pump (Figure 5.19) a well-structured model will be expected to have similar streams A and B which is also an indication of the model convergence.

Pump: Pump is used between states A and 2 (Figure 5.19). The only input to the pump is pressure change. Sometimes, the efficiency of the pump could be stated. However, since the power consumption of the pump is insignificant within the system, the default value of 100% isentropic efficiency is used. Meaning that the entire work of the pump is added to the fluids' enthalpy. Mass flow rates and concentration of weak solution are the require input to the pump. The mass flow as given by the manufacturer is 9.92×10^{-5} kg/min while mass concentration of LiBr and Water are 0.574 and 0.426 respectively.

Valves: Valves are used as the pressure changers and they are used twice within the systems: states 8 and 9; 6 and 12. The only input for the valves are the exit pressures.

Solution-Heat Exchanger: Solution heat exchanger is used once in the system (Figure 5.17). Heat is transfer from stream 5 coming from the generator to stream 2 which exit the pump. Resulting in a further cooling of stream 5 before being moving to the absorber.

Three general approach used in modelling of heat exchanger are (Herold et al., 1996) pinch point specification, UA (product of heat transfer coefficient and area of exchanger) model and effectiveness model. However, the use of effectiveness has been shown to be simple and suitable for modelling of cycles to avoid complexity and difficulties in simulation convergence (Ibid). Thus, the inputs to the exchanger are pressure and its temperature. To do this, the hot stream was made to transfer heat to the cold stream. However, the two inlet temperatures are known, and one of the other two exit temperatures was determined using heat exchange effectiveness imposed on the model with calculator block. The used heat exchanger effectiveness (ε) is 0.63 (Kakac et al., 2012) and it is implemented in the Aspen Plus calculator as indicated in the equation 5.41 while the Temperatures 2,5,and 6 are as indicated in the Figure 5-17.

$$\varepsilon = \frac{T_5 - T_6}{T_5 - T_2} \qquad (5.41)$$

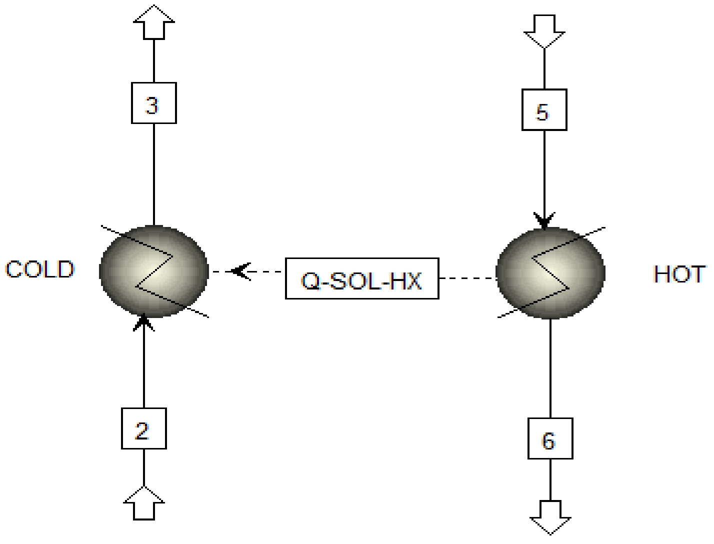


Figure 5-17: Solution-solution heat exchanger

Condenser: The condenser is also simulated as heat exchanger. It is made to reject heat to the ambient. The ambient temperature of 25^{0}C is used. The pressure drops of 38.3 kPa as indicated by the manufacturer is assumed. A pinch temperature was specified to be 5^{0}C.

Absorber: The absorber is also simulated as heat exchanger. It is made to reject heat to the ambient at 25^0C. The pressure drop is assumed to be 38.5 kPa while the only input used was the vapour quality of the hot stream which is assumed 0 at the exit.

Evaporator: The evaporator is also modelled as heat exchanger. It is made to reject heat to the chilling water which is made to enter at 12.5^0C and exiting at 7^0C as often specified by the absorption chiller manufacturers. The pressure drop is assumed to be 52.6 while the pinch temperature was specified to be 2.5^0C.

Generator: Modelling the generator is more complex than the other components since it, in addition to heat rejection or addition, involves fluid separation (Somers, 2009). The generator is modelled with a shell and tube heat exchanger and a flash (Figure 5-18) of Aspen-plus. The general assumption usually used in de-sorber modelling is to assume that the temperature of the vapour outlet stream 7 is the same as the saturation temperature of strong solution stream 5. The mass fraction of exiting vapour stream 7 and liquid stream 5 with their temperature is also assumed to be a function of the temperature of heat input (ibid).

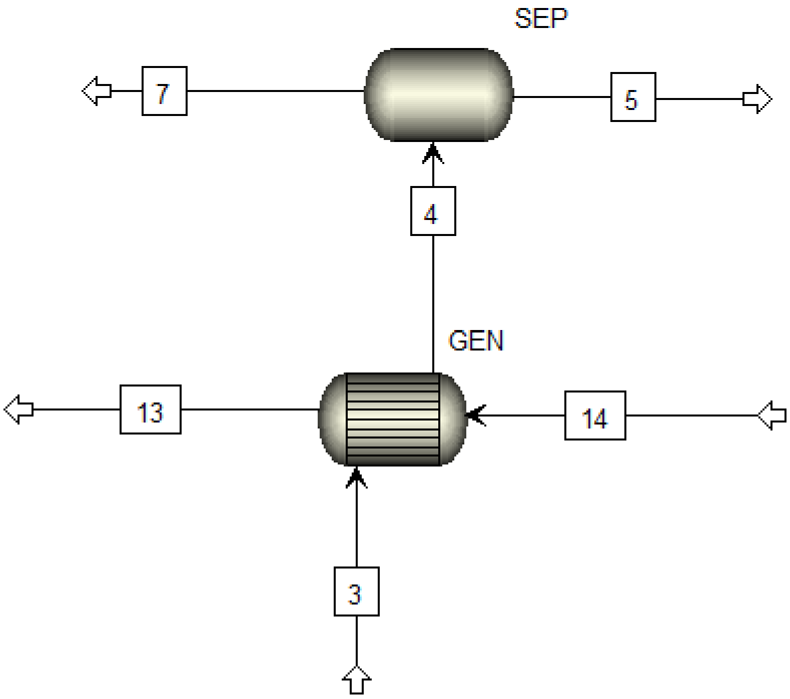


Figure 5-18: Absorption cycle generator.

Heat input is added with the heat exchanger and its input are 95.8 kPa pressure drop and both inlet and exiting temperatures of hot stream. With these, the require flow rate of water can be determined since its duty of 25.1 kW is known (Yazaki Corporation Company, 2017). A flash is then used to separate the resulting mixture (stream 4) into liquid (stream 5) and vapour (stream 7) phases.

5.3.3.4: Property method selection

The most critical step in Aspen simulation is the selection of the appropriate property method which would be used to estimate the thermodynamic data of the participating fluids. Look-up tables are not used in Aspen and the user is at liberty to, based on the operating thermodynamic conditions and fluid properties, select the appropriate property method. Therefore, there is an intrinsic error in modelling with Aspen if property method is not carefully selected (Bonab et al., 2015), (Somers et al., 2008). Earlier modelling of LiBr-water cycle by Somers et al., (2008); Darwish et al., (2008) and Karamangil et al., 2010) show ELECNRTL equation of state with NRTL property method as being the best fit in predicting thermodynamic behaviours of LiBR-water fluids within the operation condition of the absorption cycle. Thus, ELECNRTL property method is selected for this study. The complete AP model of the chiller is presented in the Figure 5-19

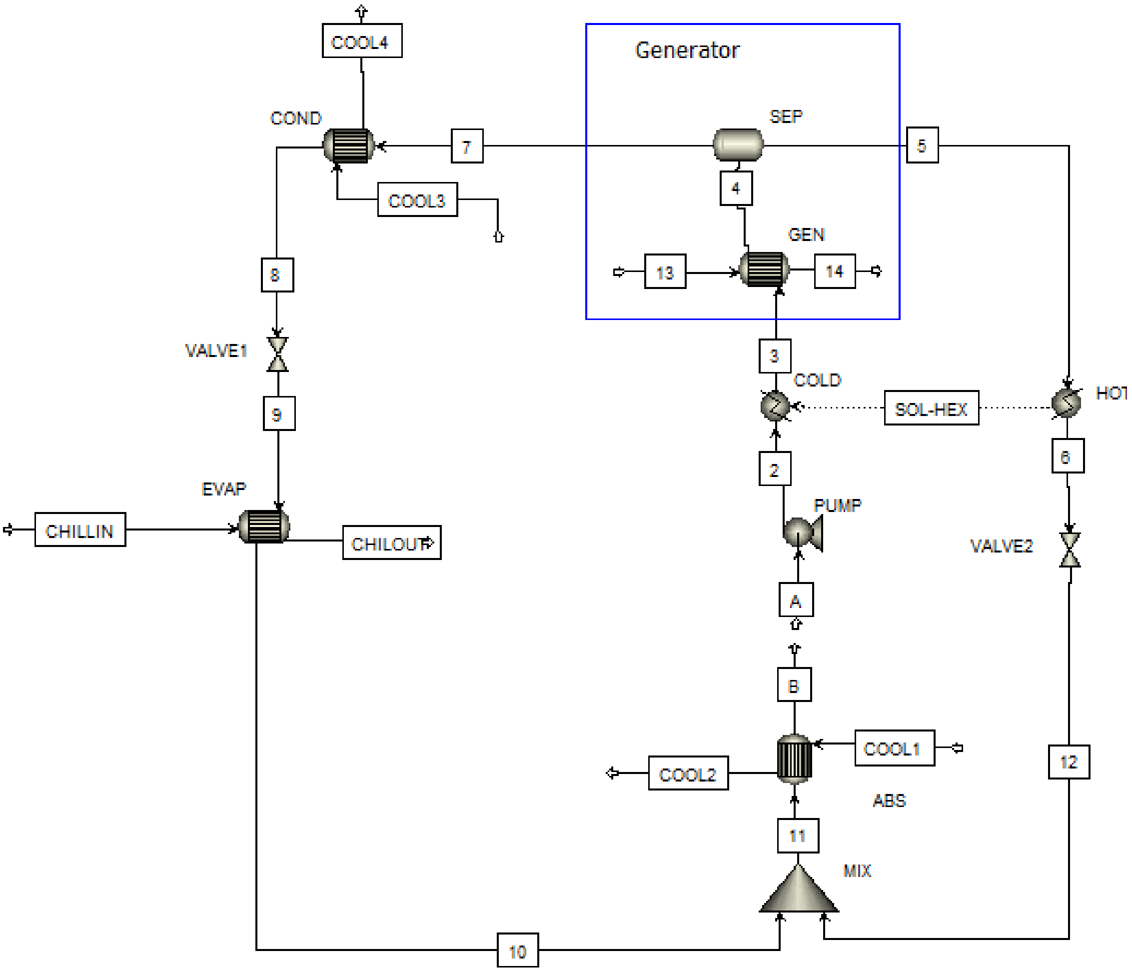


Figure 5-19: AP model of the chiller.

5.3.4 Modelling of drying unit

Drying is simulated as a cross flow convective cabinet dryer with the cross-sectional area of drying trays and residence time details as that of Atesta dryer (Boroze et al., 2014). It is a propane fuelled dryer common in the Sub-Saharan African region. However, it is proposed that the propane is replaced with exhaust gas using a heat exchanger. The dryer is modelled for drying of cassava cake (40% moisture content on wet basis) to high quality cassava flour (HQCF) (10% wet basis). Cassava cake is represented as starch and cellulose and modelled as conventional solid streams with Particle Size Distribution (CIPSD) since it is both inert and particulate. Similar to Atesta dryer, the drying temperature and residence time are set at 65^0C and 24 hours respectively. The duty or available temperature of exhaust only need to be supplied and this will allow the mass flowrates of cassava cake to be determined. Aspen modelling of the dryer is shown in the Figure 5-20

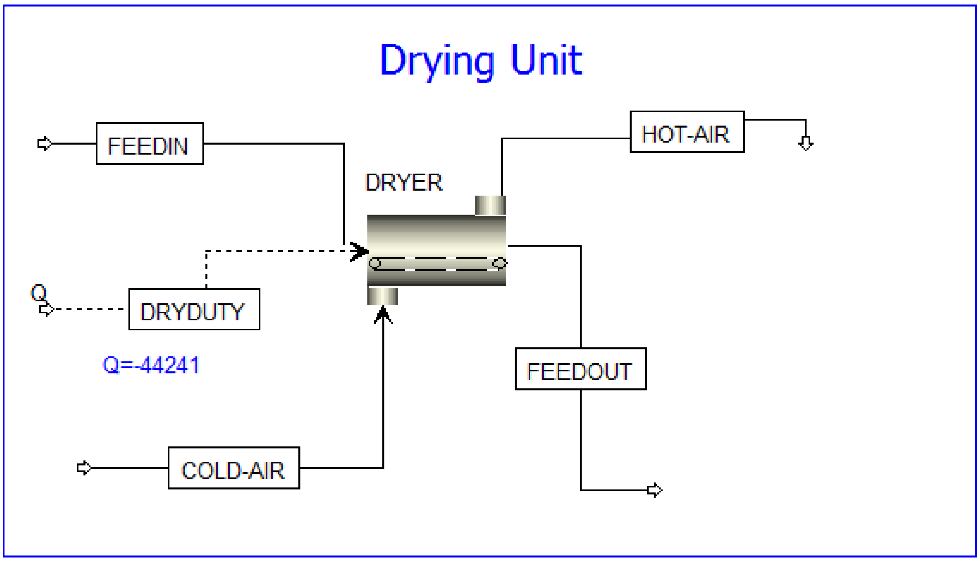


Figure 5-20: Aspen modelling of the drying unit

5.3.5 Process simulation of biogas cleaning unit

The water scrubbing unit was modelled with the compressor, column, pressure valve, flash and mixer components of Aspen Plus. The water scrubbing unit is design based on the available biogas estimated at 200 kg/hr. Raw biogas at atmospheric pressure is first compressed via two staged reciprocating compressors to 5-10 bars. It is then air cooled and sent to the absorption column where it enters from the bottom. Pressurised water is also pumped in from the top of the column which is packed with bed materials to increase both distribution and retention time of the fluids. Cleaned biogas is collected from the top of the column, dried and stored at 2 bars before being used for the ICE. The CO_2 rich liquid is first pass through a flash at reduced pressure which led to the recovery of a fraction of CH4 trapped in the CH4 rich water. The gaseous part of the stream is returned to the first compressor while the liquid component proceeds to the stripper where it is made to enter from the top. Atmospheric air is also compressed to 2 bars and used for the stripping in the regeneration column. NRTL property method is adopted for the estimation of the thermodynamic properties of the fluids and the columns were modelled with the Radfrac modules of the Aspen Plus without condenser and reboiler. The effects of operational parameters such as the influence of pressure, regeneration temperature, air flowrates and the ratio of water flow rates to gas flowrate on the CO_2 removal efficiency and methane loss were analysed. The CO_2 removal efficiency and percentage methane loss (Cozma et al., 2015); (Nguyen et al., 2018) were evaluated from equations 5.40 and 5.41 respectively.

$$CO_{2_{RE}} = \left(\frac{V_{CO_{2_{rawbio}}} - V_{CO_{2_{cleanbio}}}}{V_{CO_{2_{rawbio}}}}\right) x\ 100 \qquad (5.40)$$

$$CH_{4_{loss}} = \left(\frac{CH_{4_{exhaust}}}{CH_{4_{rawbio}}}\right) x\ 100 \qquad (5.41)$$

Where $CO_{2_{RE}}$ is the CO_2 removal efficiency (%), $V_{CO_{2_{rawbio}}}$ is the mol flow rate (kmol/hr) of CO_2 in the raw biogas, $V_{CO_{2_{cleanbio}}}$ the mol flow rate (kmol/hr) of CO_2 in the cleaned biogas, $CH_{4_{loss}}$ is the loss of methane (%), $CH_{4_{exhaust}}$ the mol flow rate (kmol/hr in the exhaust gas from the stripper while $CH_{4_{rawbio}}$ represents the mol flow rate (kmol/hr) of CH_4 in the raw biogas. Inputs and assumptions used for the upgrading unit are indicated in the Table 5-10

Table 5-10: Inputs used for the biogas cleaning system

	Components	Values
Raw biogas	Flow rate	Determines by available biogas
	Temperature (C)	25
	Pressure (bar)	1
Compressor	Isentropic efficiency	85%
	Working pressures	2 bars for the first compressor and 10 bars for the second compressor.
Absorption column	Number of stages	2 stages
	Height (m)	3
	Diameter (m)	0.3
	Pressure (bar)	10

	Temperature	25
	Packing bed	Metal balls
	Raw biogas to stripping water ratio	2:3
Valve	Valve	Discharge pressure
	Number of stages	2 stages
Stripping column	Height (m)	3
	Diameter (m)	0.3
	Pressure (bar)	1
	Temperature (C)	25
	Stripping air to CH_4 rich water	10:1
Flash	Pressure (bar)	3
	Temperature (C)	25
Stripping air	Pressure (bar)	1
	Temperature (C)	25

5.4 Results and discussion

5.4.1 Cattle market residue quantification

5.4.1.1 Number of cattle in the market

As noted in the section 5.2.1.1, quadrat sampling was used to obtain the number of cattle per unit area summary of which is presented in the Table 5.11.

Table 5-11: Land utilisation and number of cattle in the market.

Particulars	Quantity

Market size	5 acres
Used for cattle marketing	3 acres
Used for other purposes	2 acres
Quadrat size	18.3m^2
Quadrat per acre	12
Average number of cattle per quadrat	30
Average number of cattle in the market	1,080

5.4.1.2 Estimation of daily waste generated

Haven estimated the land mass and number of cattle in the market, it is required to evaluate the daily cattle waste generation which is to be used as feed stock for energy recovery. As noted earlier, two quadrats are cleaned, and the result is used to determine daily waste produced in the market as shown in the Table 5.12.

Table 5-12: Daily waste generation in the market

Particulars	Quantity
Cleaning frequency	weekly
Size of quadrat	18.3m^2
No of quadrat per acre	12
No of quadrats in 3 acres	36
No of pans per quadrats	245
Average weight per pan	8.2Kg
Weekly waste per quadrat	2009Kg
Daily waste per quadrat	287Kg
Daily cattle waste generated in the market	10,332Kg

From Tables 5.11 and 5.12, the daily waste produced per cattle is about 9. 57 kg. The figure is less than between 26 to 30 kg/day bio-waste estimated per cattle head in Nigeria (Sangodoyin, 1996) (Ngumah et al., 2013). However, this is understandable considering that the cattle are on transit and feeding is not the same as that of the farm. Besides, bovine and slaughterhouse waste is also included in the previous estimations.

5.4.1.3 Waste characterisation

The composition of the waste as expressed in percentage is shown in Table 5.13.

Table 5-13: Characterisation of cattle market waste

Components	Percentage (%)
Organic waste	98.4
Plastic bags	0.8
Plastic bottles	0.4
Woods	0.2
Paper	0.1
Textiles	0.05
Others	0.05

As shown in the table, putrescible constitutes the highest percentage of the waste (98.4%) and it is followed by plastic bottles, plastic bags, woods, paper and textile which are 0.8%, 0.4%, 0.2%, 0.1% and 0.05% respectively. The putrescible component of the waste is higher than 68.98% recorded for 40 sampled markets by Oyelola and Babatunde (Oyelola and Babatunde, 2008) in Lagos metropolis. The difference can be attributed to the specialised nature of the market sampled. The present study is conducted in the livestock market while general markets were used for the former study. Besides, the different in the lifestyles of rural and urban dwellers can also contribute to the differences. However, similar trend is observed in the use of plastic bags and plastic bottles. This is because packaged water is cheaper in plastic bags than bottles. Hence, more preference for plastic bags.

5.4.1.4 Suitability of the waste for AD system

The cattle market waste is currently available and in the form that could be used for AD system. However, the impurities such as plastics, packing bags, tree shrubs and sands may need to be removed onsite before it can be suitable for AD substrates.

5.4.1.5 Challenges in data collection

The following are the challenges encountered during collection of data from the cattle market:

- Fulani traders are culturally biased towards removing of cattle dung as it is believed it could lead to death of their cattle.
- Cattle traders are not willing to divulge information on the numbers of cattle in the market as it is thought the data could be used by the government for tax related issues.

However, these were resolved after they were given the assurance that the data would be strictly used for research purpose.

5.4.2 Proximate analysis of the cattle waste

The proximate and ultimate composition of the cattle waste are presented in the Table 5.14**Error! Reference source not found.** and Table 5.15 respectively. Compositions of the farm residues are indicated in the Table 5-5. Notwithstanding the heterogeneous nature of the market waste, its composition, though tends more towards cattle manure, is in agreement with published data for biomass (Shen et al., 2015; Lin et al., 2010; Xin et al., 2018; Chen et al., 2017). Cellulose, hemicellulose and lignin contents of the market waste were found to be between 40-60%; 20-40% and 10-25% respectively reported for biomass (Lin et al., 2010). However, these values of the lignocellulose materials are slightly out of range when compared with pure cattle manure. This is expected since the waste is a combination of manure and leftover lignocellulose grass being fed to the cattle in the market. Values such as crude protein and crude fat also fluctuate between values reported for pure grasses and wet cattle dungs (Kiyasudeen et al., 2015; Mohammed et al., 2015).

Table 5-14: Proximate analysis of cattle market waste.

	Properties	Values
Proximate analysis	Volatile matter (wt. % db)	60.30±2.50
	Fixed carbon (wt. % db)	20.55±2.10
	Ash content (wt. % db)	19.15±1.70
Composition analysis	Raw Protein (wt. % db)	6.60±0.66
	Raw fat (wt. % db)	2.30±0.67
	Ash content (wt. % db)	19.15±1.70
	Carbohydrate (by difference)	71.95±2.50
Carbohydrate components	Cellulose	26.70±2.30
	Hemicellulose	13.40±2.60
	Lignin	13.40±2.40
	Sugar & starch (by difference)	18.45±2.70

Table 5-15: Ultimate analysis cattle market waste (ash free)

Properties	Values
Carbon (wt. % db)	50.38±1.20
Hydrogen (wt. % db)	7.02±0.75
Nitrogen (wt. % db)	3.55±0.67
Sulphur (wt. % db)	0.75±0.07
Oxygen (wt. % db; by difference)	38.30±1.55

5.4.3 Theoretical determination of biogas and energy yield

The elemental percentage composition of the waste is known. Therefore, given the empirical formula and atomic weight of the compositional elements, the theoretical biogas generation and energy yield from the waste could be calculated with Buswell equation shown in equation 5.35.

From **Error! Reference source not found.**, the percentage composition is 50.38; 7.02; 38.30; 3.55 and 0.75 for Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) and Sulphur (S) respectively. Hence, elemental composition by weight for the compound will be:

$$C_{50.38}H_{7.02}O_{38.30}N_{3.55}S_{0.75}$$

Assuming 100g of the sample and given their atomic weight (C=12, H=1, O=16, N=14, S=32), the empirical formula of the compound is obtained as:

$$C_{179}H_{300}O_{102}N_{11}S_{1}$$

From equation 5.35, the theoretical biochemical methane potential (TBMP) of the cattle market waste is 0.256.3 ml/gVS.

The process is repeated for cassava, cashew; maize and tomato residue to obtain their specific theoretical methane generation potentials. The values obtained are compared with empirical experimental studies from Prabhudessai et al. (2013); Okudoh et al. (2014); Rahman, (2011); Li et al. (2013) and Alnakeeb et al. (2017) for cashew apple waste, cassava residue, cattle market waste, maize residue and tomato waste respectively which is presented in the Figure 5-21.

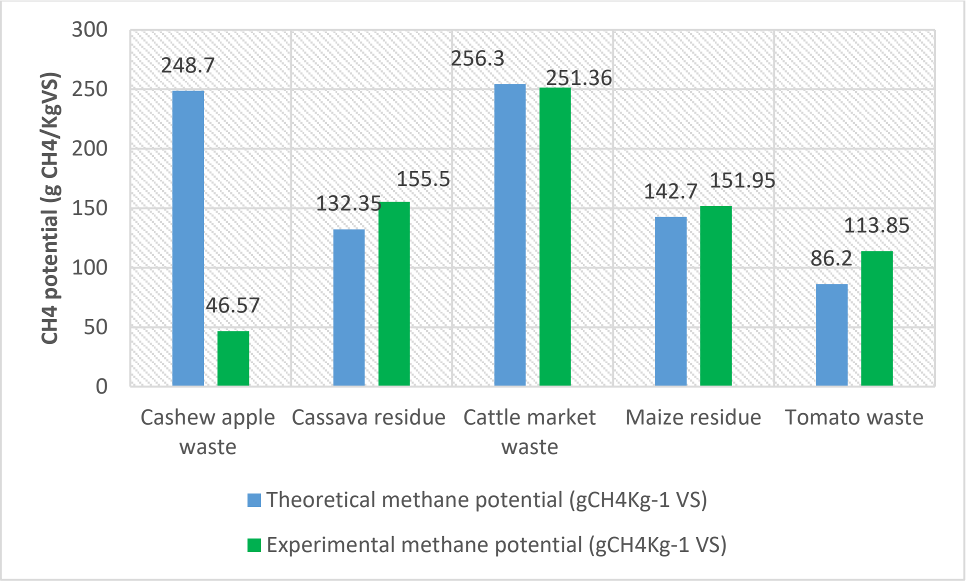


Figure 5-21: Specific methane potential of the farm residues.

From Figure 5-21 it is observed that the differences between values predicted by Buswell equation and experimental values of individual farm residues are not too much but within ranges of percentage differences reported by earlier studies. An exception of this is cashew apple waste which is grossly over predicted. A potential reason for this error might be because the experimental study was done with fresh cashew apple residue (residue with juice) whereas the ultimate analysis report used for the theoretical methane potential used dried cashew apple residue.

Since these differences are not too much, it is therefore decided that these values can be used as input for the Aspen Plus simulation. Based on the harvesting traditions of the study area where cassava is regarded as stored wealth. Harvesting is therefore done when needed especially for feeding and sales. Thus, it is assumed that the cassava waste and cattle market wastes are available throughout the year while availability of cashew apple residue, maize Stover and tomato wastes depend on the harvesting seasons. Three biogas production scenarios are therefore considered: 1) Co-digestion of cattle market waste with cassava and cashew apple residue; 2) Co-digestion of cattle market waste with cassava and maize residue and 3) Co-digestion of cattle market waste with cassava and tomato residues. Details of these are discussed later in the next section.

5.4.4 Validation of the digestion system

A1) Brewery spent grain-thermophilic: The result of the modelling at thermophylic condition is presented in Table 5.16. The model is in good agreement with experimental values for biogas production. It only underpredicts specific biogas production by -3.7%. A 10% difference was reported normal for laboratory experiment while as much as 25% may be acceptable for the industrial process (Nguyen, 2014). However, the model poorly predict biogas composition. It underestimated methane production by -28%. However, the underpinning objective of the model is for the quantification of biogas rather than the prediction of biogas quality.

Table 5-16. Thermophylic production of biogas from brewery spent grain

	Experiment	Simulation	% diff.
Particulars	Thermophili	Thermophilic	-
Temperature C	55	55	-
Daily loading rate (l)	0.2	0.2	-
Digester volume (M^3)	0.005	0.005	-
OLR (g_{vs}/day)	5	5	-
HRT (days)	25	25	-
Percentage methane	65%	46.75	-28.07
Biogas production (l/d)	2.697	2.512	-6.85
Specific biogas production (L/gVS)	0.5394	0.5024	-3.7

A11): Brewery spent grain- mesophilic: Similarly, the model perfectly estimates biogas production at mesophilic temperature as shown in Table 5.17. However, it is unable to predict the biogas composition. The methane content was expected to be higher in thermophylic condition than mesophilic process (Chae et al., 2008). However, a reverse trend was observed. Methane composition is overpredicted by 16.36%.

Table 5-17:Mesophilic production of biogas from brewery spent grain

	Experimental	Simulation	% diff.
Particulars	Mesophilic	Mesophilic	-
Temperature C	35	35	-
Daily loading rate (l)	0.2	0.2	-
Digester volume (M^3)	0.005	0.005	-
OLR (g_{VS}/day)	5	5	-
HRT (days)	25	25	-

Percentage methane (%)	55	64	+16.36
Biogas production (l/d)	3.00375	3.00352	-0.0078
Specific biogas production (l/gVS)	0.60075	0.60070	-0.0083

B) Cow manure

The thermophilic prediction of the cow manure digestion is shown in Table 5.18. Again, the model is reasonable in the quantification of biogas production with the percentage difference, of specific biogas production, between experimental study and the model less than 1%. The estimation is in the same range with the value reported by Rajendran et al (Rajendran et al., 2014) for the cow manure and the Aspen Plus modelling of the food waste digestion by Nguyen (Nguyen et al., 2014).

Table 5-18: Thermophylic production of biogas from cow manure

	Experiment	Simulation	% difference
Particulars	Thermophili	Thermophilic	-
Temperature C	55	55	-
Digester volume (m^3)	0.005	0.005	-
OLR (L/day)	0.33	0.33	-
HRT (days)	15	15	-
Percentage methane	49.29%	47.75	-3.12
Specific biogas production (L/kgVS/d)	353.5	356.56	+0.89

C) Sugar beet pulp

The similar trend to the above was also observed for the sugar beet pulp where the model's specific biogas was 0.620 L/gVS/day which is 6.6% under-predicted compared to the experimental study. Again, the specific methane potential was poorly predicted in excess of 15.30% to the 0.345 LCH4/ gVS /day.

5.4.5 Modelling of cattle market waste and its co-digestion

5.4.5.1 Thermophilic digestion of cattle market waste

Having satisfied with the results of the model validation where the specific biogas production is reasonably predicted. The model was then used for the AD process of cattle market waste with the composition presented in the Table 5.14. The 10,332 kg/day waste is mixed with water to obtain a 10% total solid since AD processes is known to perform optimally at this range (Zhang et al., 2007; Lehtomäki et al., 2007a). This gives a final daily feed rates of 67, 157kg/day. The required daily volume is 64.58 m^3/day using 1040 kg/m^3 as the substrate density (Castellanos et al., 2015). The kinetics constants presented in the Appendix 4 was adopted for the thermophilic condition. The hydraulic retention time and digestion temperature of 15 days and 55^0C were adopted to obtain the biogas composition presented in Table 5-19. Biogas compositions varies considerably with substrate (Fantozzi and Buratti, 2009; Rasi, 2009) used. The composition predicted by the model for agricultural wastes is within the values reported from the previous studies. A biogas composition of 40-70%; 25-55%; 0-1%; 0-10; 0-5%; 0-2%, 0-1% and less than 1% methane, CO_2, ammonia, water, nitrogen, oxygen and hydrogen sulphide respectively was reported for food and agricultural waste by Rasi (2009). A similar composition was reported by (Planet Biogas Solutions, 2017) and (Arrhenius and Johansson, 2012) with the exception of water content that is over predicted by 11.12%.

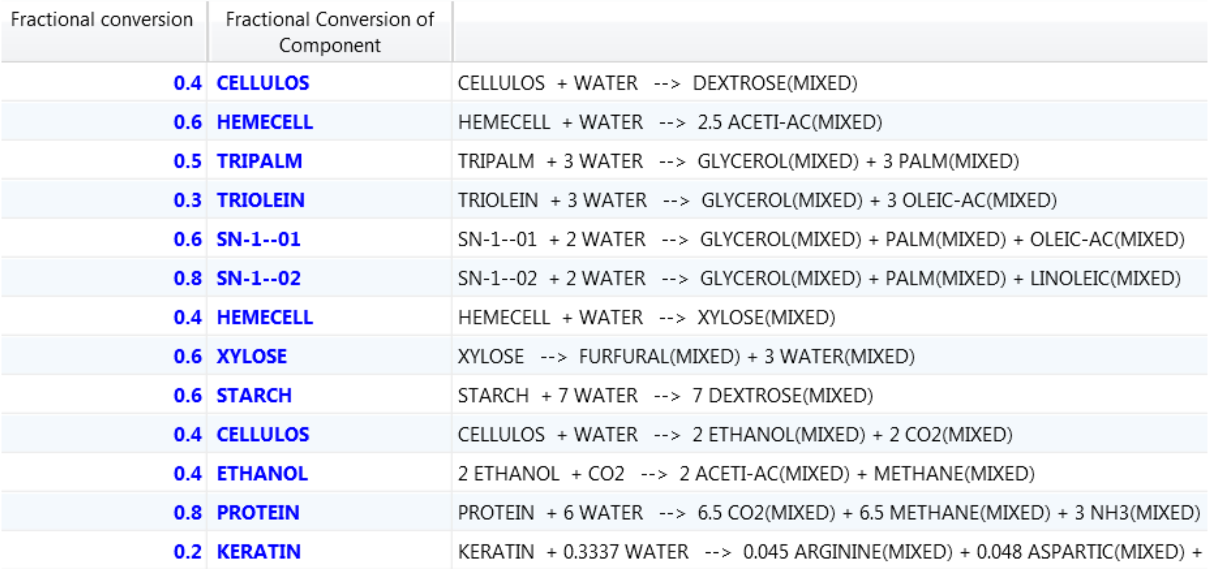
Table 5-19: Biogas composition of thermophilic system

Particulars	Composition (% vol)
Water	11.12
Methane	50.60
CO_2	36.17
Hydrogen	0.40
Ammonia	0.80
Hydrogen sulphide	0.87

As noted earlier, in addition to temperature, anaerobic conversion of biomass to biogas could be affected by factors such as extent of hydrolysis, pH inhibition, organic loading rates, and hydraulic retention time. Thus, details of these factors are discussed below:

1. **Hydrolysis:** This is a temperature dependent and an extracellular stage of AD process which has been reported to be a limiting stage of AD bioconversion whose optimisation differs from the rest intracellular stages of the digestion (D. J. Batstone et al., 2002; Kranert et al., 2012). Its optimisation approach is substrate pre-

treatments: thermal; chemical, biological and size reduction. All of these noticeably altered the extent of conversion of the major components of substrate such as protein, carbohydrate and lipids (Aslanzadeh et al., 2011). Besides, disintegration of these components are not occurring at the same time with carbohydrate being the fastest follow by fat while protein is the slowest (Miron et al., 2000). Therefore, hydrolysis of the major components into monomers, amino acids and fatty acids is presented in the Figure 5-22. The fractional conversion is then varied (±20%) to check its effect on the specific biogas production and its result is presented in Figure 5-23. The fractional conversion of each of the major component is modelled as the extent of conversion of one of its representative polymer structures. For example, the conversion of hemicellulose, triglyceride, and gelatine symbolises the fractional conversion of carbohydrate, fat and protein respectively.



Fractional conversion	Fractional Conversion of Component	
0.4	**CELLULOS**	CELLULOS + WATER --> DEXTROSE(MIXED)
0.6	**HEMECELL**	HEMECELL + WATER --> 2.5 ACETI-AC(MIXED)
0.5	**TRIPALM**	TRIPALM + 3 WATER --> GLYCEROL(MIXED) + 3 PALM(MIXED)
0.3	**TRIOLEIN**	TRIOLEIN + 3 WATER --> GLYCEROL(MIXED) + 3 OLEIC-AC(MIXED)
0.6	**SN-1--01**	SN-1--01 + 2 WATER --> GLYCEROL(MIXED) + PALM(MIXED) + OLEIC-AC(MIXED)
0.8	**SN-1--02**	SN-1--02 + 2 WATER --> GLYCEROL(MIXED) + PALM(MIXED) + LINOLEIC(MIXED)
0.4	**HEMECELL**	HEMECELL + WATER --> XYLOSE(MIXED)
0.6	**XYLOSE**	XYLOSE --> FURFURAL(MIXED) + 3 WATER(MIXED)
0.6	**STARCH**	STARCH + 7 WATER --> 7 DEXTROSE(MIXED)
0.4	**CELLULOS**	CELLULOS + WATER --> 2 ETHANOL(MIXED) + 2 CO2(MIXED)
0.4	**ETHANOL**	2 ETHANOL + CO2 --> 2 ACETI-AC(MIXED) + METHANE(MIXED)
0.8	**PROTEIN**	PROTEIN + 6 WATER --> 6.5 CO2(MIXED) + 6.5 METHANE(MIXED) + 3 NH3(MIXED)
0.2	**KERATIN**	KERATIN + 0.3337 WATER --> 0.045 ARGININE(MIXED) + 0.048 ASPARTIC(MIXED) +

Figure 5-22: Hydrolytic fractional conversion of substrate components

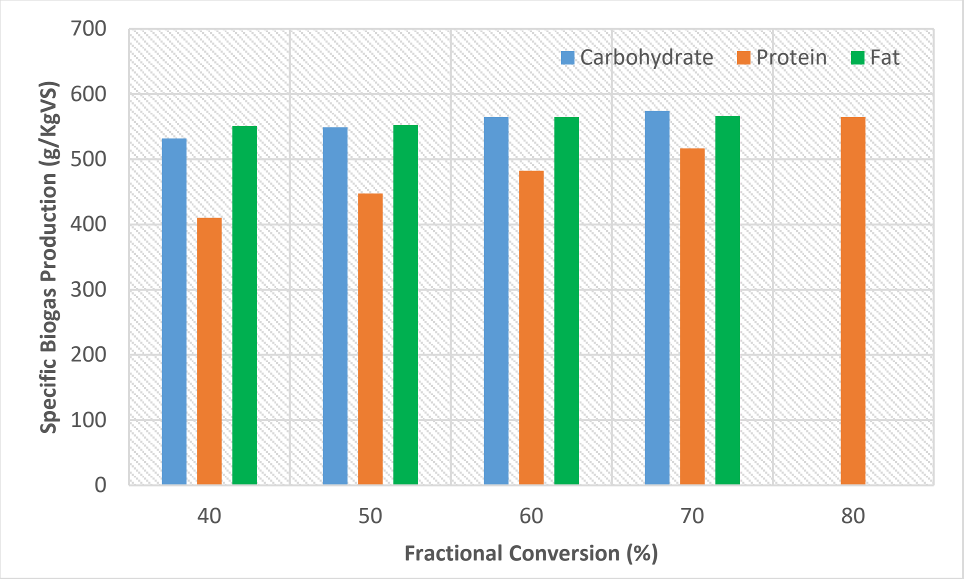


Figure 5-23: Effect of fractional conversion on specific biogas production

The specific biogas production is observed to increase with increasing extent of conversion. This is particularly more pronounced with protein conversion. However, the percentage methane content of the biogas reduces with increasing fractional conversion of protein and becomes negligible above 80% fractional conversion. This might be because protein conversion is favoured by methanogen condition which is alkaline while conversion of carbohydrate is favoured by acidogenesis condition (Miron et al., 2000). Meanwhile, the conversion of carbohydrate plays prominent role in methane composition of biogas. Thus, at elevated pH, less carbohydrate is hydrolysed while more soluble protein is converted. This altered the system's carbon-nitrogen ratio and led to reduction in methane production. Besides, it is seen that the extent of conversion of crude fat do not have a significant effect on the specific biogas generation. A shift in conversion from 40% to 70% only increase biogas production by 2.7% which may be attributed to the low concentration of crude fat in the original biomass composition.

2. **Organic loading rate (OLR):** The metabolic activities of the microbes involves feeding on microbes to produce biogas as the desirable by-product. Hence, OLR represents the daily input of the organic feedstock into the digester which must be within a particular threshold (Ward et al., 2008) to avoid negatively impacting the AD process. The daily loading rate was varied from 2, 3, 4, 5, 6, 7 gVS(Lday)$^{-1}$ and the result is depicted in the Figure 5-24. The specific biogas is observed to increase with

the increasing OLR until 5 gVS.(Lday)$^{-1}$ and thereafter decreases. The proportion of the major component such as cellulose in the effluent also increases correspondingly as the OLR increases from 5 to 7 gVS.(Lday)$^{-1}$ indicating that the biomass input is in excess of what is required by the bacteria load.

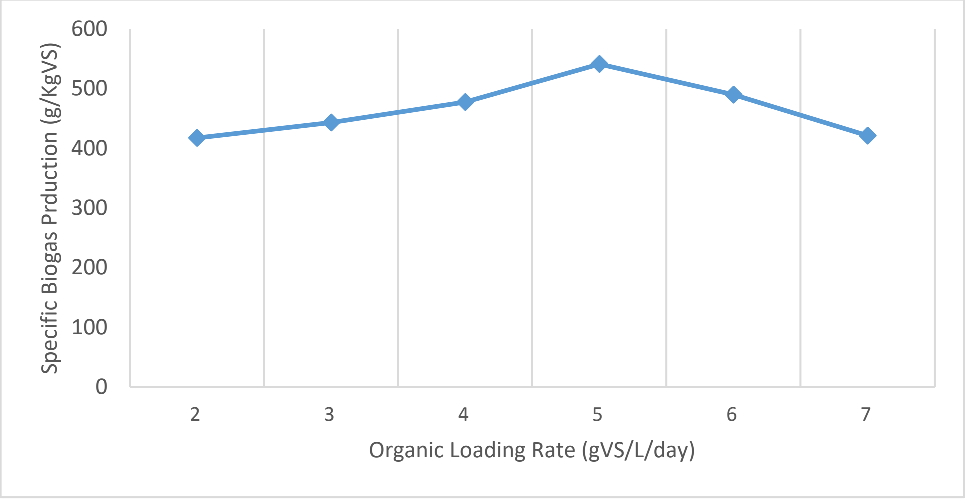


Figure 5-24: Variation of biogas production with changing OLR

3. **Hydraulic retention time (HRT).** This is a parameter that determines the contact time between the microbes and substrates. Again, this is also substrate specific and needs to be maximised (Miron et al., 2000). Too much retention time can lead to the substrate insufficiency while microbes wash is the major problem with the shorter retention time. The HRT was varied between 5 and 20 days for the thermophilic system as indicated in Figure 5-25 while 15 to 30 days was checked for the mesophilic system. The maximum specific biogas production was obtained at 15 days and 28 days respectively for the thermophilic and mesophilic system.

Figure 5-25: Effect of varying retention time on specific biogas production

5.4.5.2 Mesophilic digestion of cattle market waste

The process is also performed with the same reactors of Aspen Plus: Rstioc for the hydrolysis and RCSTR for acidogens, acetogens and methanogens dependent processes. Chemical reactions, activation energy, and kinetic equations are also similar. The activation energy is temperature dependent. However, just like ADM1, it is presumed same for the temperature between 0^0C and 60^0C (D. J. J. Batstone et al., 2002). Hydrolysis is also temperature dependent and expected to increase with increasing temperature. Hence, hydrolysis reactor is modelled with 20 to 30% changing in the fractional conversion. The kinetic constants in ADM1 is mainly for the thermophilic system. Therefore, the kinetic constants used in the FORTRAN blocks of the mesophilic system are sourced from the published empirical studies and it is shown in the Appendix 5. The waste was mixed with water to obtain a 10% total solid. The digestion temperature of 35^0C and 28 days HRT was adopted.

Composition of biogas produced is indicated in the Table 5.20. Again, the water composition is over predicted while other compositions are within values reported for biogas from agricultural residues (Rasi, 2009). The specific biogas production is 517.84 g/kgVS which is 4.3% less than the value obtained from the thermophilic digestion system. The predicted methane composition is 63.60%. A similar trend was reported by Gallert and Winter (Gallert and Winter, 1997) for the anaerobic digestion of food waste where, though with higher biogas production, the methane content of mesophilic process is higher than what is obtained with the thermophilic digestion process. However, since the model is generally unable to perfectly predict the biogas composition as explained in the validation section, a conservative methane composition of 55% is adopted and this value is assumed for the modelling.

Table 5-20: Biogas composition of mesophilic system

Particulars	Composition (%vol)
Water	12.15
Methane	63.60
CO_2	22.98
Hydrogen	0.25
Ammonia	0.13
Hydrogen sulphide	0.89

5.4.5.2 Sensitivity analysis digestion of cattle market waste digestion (Mesophilic)

The effects of changing in temperature and PH on the mesophilic system are presented in the Figures 5.26 and 5.27. It follows a similar trend with the thermophilic digestion. However, mesophilic digestion is observed to be more stable to PH changes than the thermophilic system in terms of the specific biogas production.

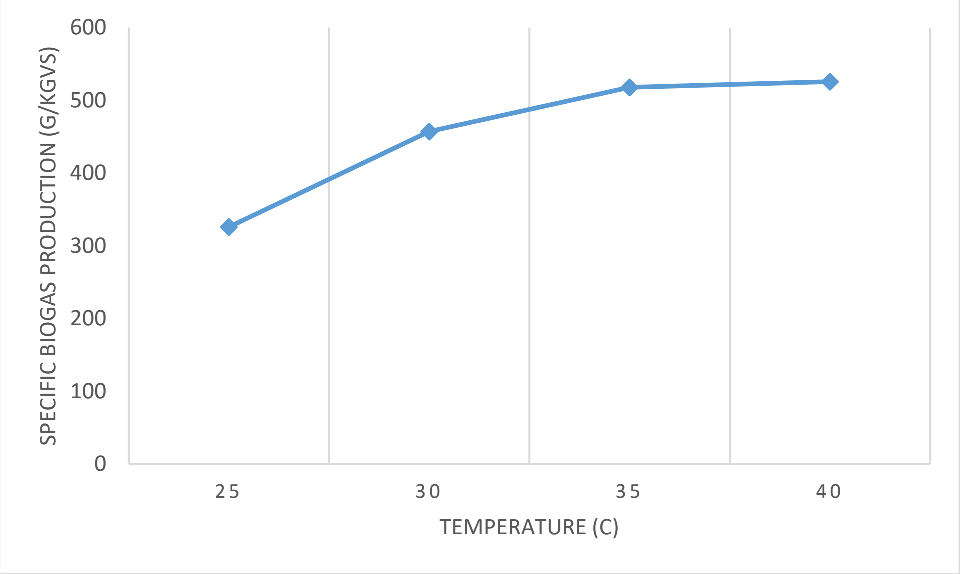


Figure 5-26: Effect of temperature changes on biogas production

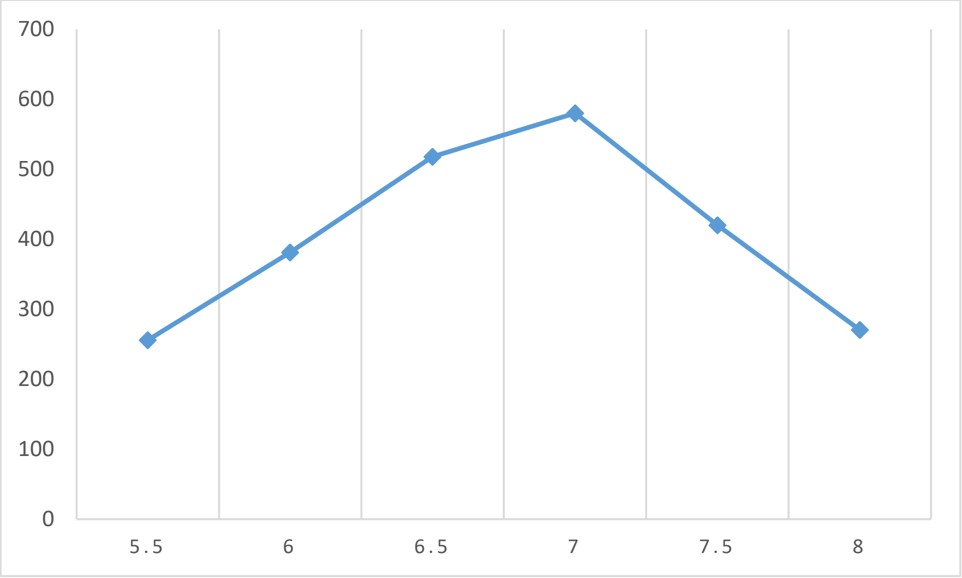


Figure 5-27: Effect of PH on biogas production

5.4.5.3 Co-digestion cattle market waste with farm residues

Co-digestion which is a simultaneous digestion of more than one substrate could be necessitated by some reasons: a) heterogeneity which could be associated with the nature of the substrate e.g. digestion of the organic fraction of the municipal solid wastes; 2) availability which could be occasioned by the seasonal variability of substrates of interest and 3) synergistic reasons where the deficiency of a substrate is compensated with another substrate e.g. animal manure which naturally have low carbon to nitrogen ratio (Nguyen et al., 2014)(Lehtomäki et al., 2007b). The farming activities of the study area is largely influenced by rainfall which subsequently controls harvesting and availability of farm residues. Therefore, co-digestion of farm residues was carried out using the below mentioned assumptions and scenarios.

Assumptions

- Cattle market waste is available daily (field survey)
- Cassava waste is available daily (harvesting tradition)
- Maize, cashew and tomato waste are seasonal.

Hence the scenarios considered:

1. Co-digestion of cattle market waste with cassava waste and cashew apple residues.

2. Co-digestion of cattle market waste with cassava waste and maize residues.
3. Co-digestion of cattle market waste with cassava waste and tomato residues

Meanwhile, the three commonly used ratios for co-digestion of biomass are wet weight, volatile solid ratios or total solid ratio (Das and Mondal, 2016). The first is adopted in this study to obtain the compositions presented in Table 5.21.

Table 5-21: Co-digested feedstocks

Properties	CCC*	CCT*	CCM*
Volatile matter (wt.% db)	71.79	74.74	70.52
Fixed carbon (wt. % db)	19.17	15.53	18.97
Ash (wt. % db)	9.04	9.73	10.52
Raw protein (wt. % db)	11.63	14.27	9.86
Raw fat (wt. % db)	7.38	10.48	8.42
Carbohydrate (wt. % db) [by	71.95	65.52	71.22
Daily substrate flow (kg)	48,889.50	48,889.50	48,889.50
Daily VS flow (kgVS/day)	12,465.00	15,220.90	22,371.24
Digester volume (m^3)	4672	4790	6390

**CCT signifies co-digestion of cassava residue, cattle market waste and tomato residue; CCM is cassava residue, cattle market waste and maize residue while CCC represents cassava residue, cattle market waste and cashew apple residue.*

Based on the results of the parametric study, thermal requirements and the quantity of biogas produced, a mesophilic digestion system is recommended for the design. Hence, the suggested digester volume is 5000 m^3 while the corresponding biogas production from the mesophilic digestion of different scenarios is presented in the Table 5.22.

Table 5-22: Analysis of biogas production from different scenarios

Particulars	CCC	CCT	CCM
Specific methane production (gCH4/kgVS)	184.45	147.22	164.72
Daily methane production (kg/day)	2299.17	2240.82	2896.97
Daily biogas production (kg/day)	4180.27	4074.21	5,267.22

Conclusion on modelling of the anaerobic digestion system: The developed anaerobic digestion process model is suitable for the prediction of specific biogas production of various biomass. It is not accurate for the estimation of biogas composition. However, the model can be adapted by anybody to reasonably quantify the biogas production from different biomass including co-digestion. User is only obliged to provide the following:

- Mass flowrate and composition of the substrate (average of individual components in case of co-digestion on wet basis; volatile solid or total solid)
- Define the temperature and pressure of the hydrolysis reactor
- Specify the digester volume and hydraulic retention time of the continuous stirred tank reactor.

5.4.6 Validation and parametric studies of the ICE

5.4.6.1 Validation of the engine-72 kWe

The gas engine is model with AP software as explained in section 5.2.2 using technical data presented in Table 5-7. The output parameters got from the Aspen Plus model is validated with manufacturer's specification (Caterpillar G3305 (Caterpillar Electric Power Inc, 2011)) as presented in the Table 5.23.

Table 5-23: Validation of simulation results with G3306 CAT Engine

Particulars	Specification	Simulation	Deviation (%)
Power (kW)	72.00	72.87±2.1	+1.2
Combustion air flowrate (m^3/h)	294.00	294.00±0.04	0.00
Exhaust stack gas temperature (C)	581.00	590.85±6.1	+1.7
Exhaust gas flowrate (m^3/h)	324.00	334.00±3.2	+3.1
Heat rejection to water jacket and	-115.00	-117.14±1.8	-4.26

The power output from simulation results deviates by 1.2% from manufacturers' specification while the stalk exhaust temperature predicted by AP is 591^0C as against 581^0C for the real engine. Unlike computational fluid dynamics, this could be attributed to the inability of AP to perfectly predict temperature discrepancies of combustion process (Ekwonu et al., 2013). However, the engine efficiency predicted by AP is 26.73% which is similar to 25.90% calculated from G3306 gas engine manufacturers' technical data (Caterpillar Inc., 2011). More so, while real engine operates at 6.85 air-fuel ratio (AFR); Aspen Plus model is unable to utilise all fuels at the given 6.85 air-fuel ratio (AFR) but 100% fuel conversion is obtained at 8.85 AFR which consequently results in increased efficiency. The efficiency of 26.73% is below the range of 28-39% (Onovwiona and Ugursal, 2006) reported for many spark ignition internal combustion engines. However, this may be attributed to its low AFR compared to around 14.1 reported for many standard engines. Nevertheless, the engine is specifically designed to work with relatively impure low grade fuels and it is expected that some of the features of the high grade fossil fuel driven engines might have been compromised during the design.

5.4.6.2 Validation of the engine-103 kWe

The result of the 103 kWe engine is presented in Table 5.24. It is observed to follow a similar trend with the 72 kW. The Aspen calculated efficiency is 30.87%.

Table 5-24: Validation of simulation results with G3406 CAT Engine

Particulars	Specification	Simulation	Deviation (%)
Power (kW)	103	103.72± 0.8	+0.70
Combustion air flowrate (m^3/h)	384	384.60±2.3	0.00
Exhaust stack gas temperature (C)	578	580.30±5.7	+0.40
Exhaust gas flowrate (m^3/h)	426	436. 65±1.7	+2.51
Heat rejection to water jacket and	-142	145. 83±5.2	-2.70

Meanwhile, since both engines have similar pattern, the results of the parametric studies on the 72 kWe is presented below.

5.4.6.3 Effect of ambient conditions of combustion air on gas engine

There exists temperature variations in Nigeria with 19^0C being the lowest in the southern coaster regions while 37^0C or above are being recorded in the North (Amadi et al., 2014) especially during hot seasons. It is therefore necessary to evaluate the effects of ambient temperature on efficiency of the gas engine. Figure 5-28 illustrates variations of the efficiency of gas engine with changing in ambient temperature. As the ambient temperature increases, the engine efficiency decreases. Unlike gas turbine where the effect is well pronounced (Wiser et al., 2010; Environmental Protection Agency, 2015), increase in atmospheric temperature do not significantly affect the efficiency of gas engine. However, the efficiency will be badly affected at temperature above 50^0C.

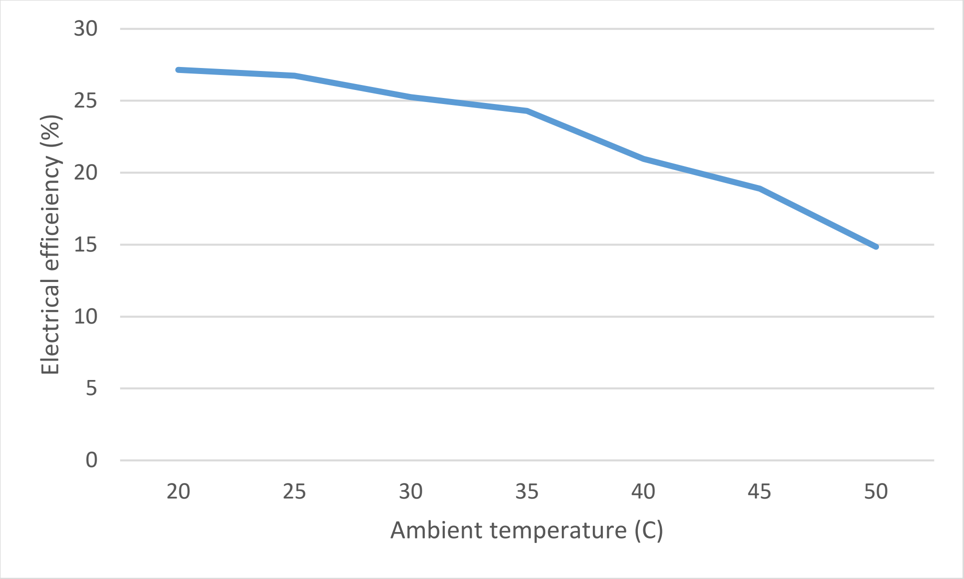


Figure 5-28: Variation of electrical efficiency with changing ambient temperature

5.4.6.4 Effect fuel composition on power output and exhaust temperature

The engine is feed with varying biogas composition to determine its effect on efficiency. Table 5.25 indicates composition of biogas tested while performance of engine with various percentage purity of biogas is presented in Figure 5-29. Energy content of fuel greatly determines the power production of gas engine. This is because heat content of fuel defines the amount of its available chemical energy that can be converted to heat and subsequently useful energy. Thus, to meet up with the electric power and heat demand of the system, it will be uneconomical to operate the system with fuel less than 65% methane purity.

Table 5-25: Composition of biogas fuel tested

S/N	Gas	Methane	CO_2
1	Base	0.705	0.295
2	Bio80	0.800	0.200
3	Bio70	0.700	0.300
4	Bio60	0.600	0.400
5	Bio50	0.500	0.500
6	Bio40	0.400	0.600

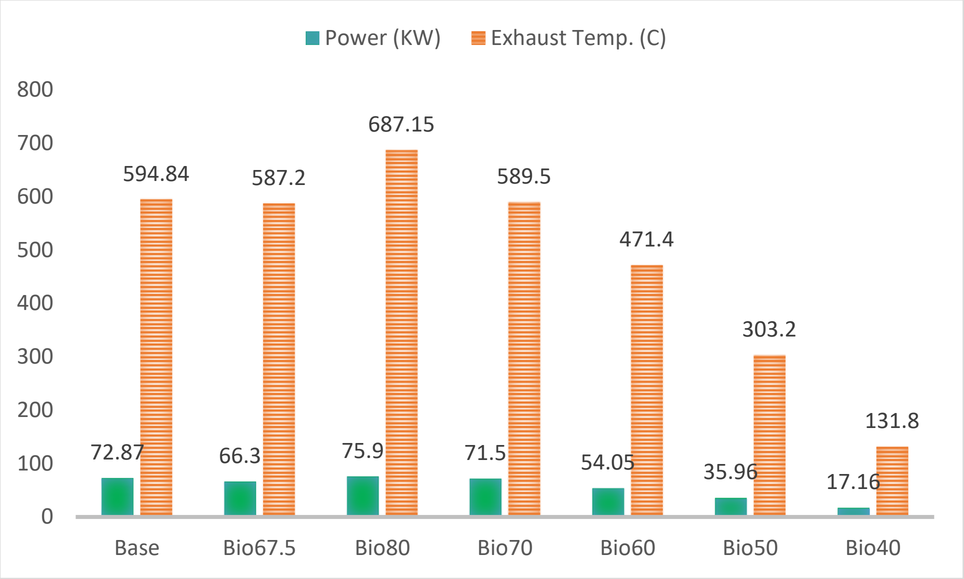


Figure 5-29: Effect of different biogas composition on power output

5.4.6.5 Effect of part load on engine efficiency

There exist variations in the consumers' energy demand throughout the day. This subsequently results in the generator's load fluctuations. Plant cycling is also thought to increase thermal and pressure stresses on power plants (Lew et al., 2013) and thereby causes damages in addition to increased environmental costs due to more emission associated with low load operation of power plants. Hence, partial load performance is an important factor in the choice of prime mover for a CHP system (Onovwiona et al., 2007). The variation of engine electrical efficiency with part loading is presented in Figure 5.30. The efficiency slightly decreases as the load reduces. A reciprocating ICE when used for power generation usually drives an harmonised generator to generate steady electrical current (Onovwiona and Ugursal, 2006). However, reducing engine load at constant speed do cause an increase in the brake specific fuel consumption of the engine. Thus, more fuel would be required per kWh of electricity produced and therefore a reduced engine efficiency. As indicated in the figure, reciprocating engines performed fairly well with part loading compared to gas turbines (Environmental Protection Agency, 2015). The difference in engine efficiency at full load and 50% load predicted by the model, at constant AFR, is only 9.8% which is consistent with values reported by (Ekwonu et al., 2013) and (Wiser et al., 2010).

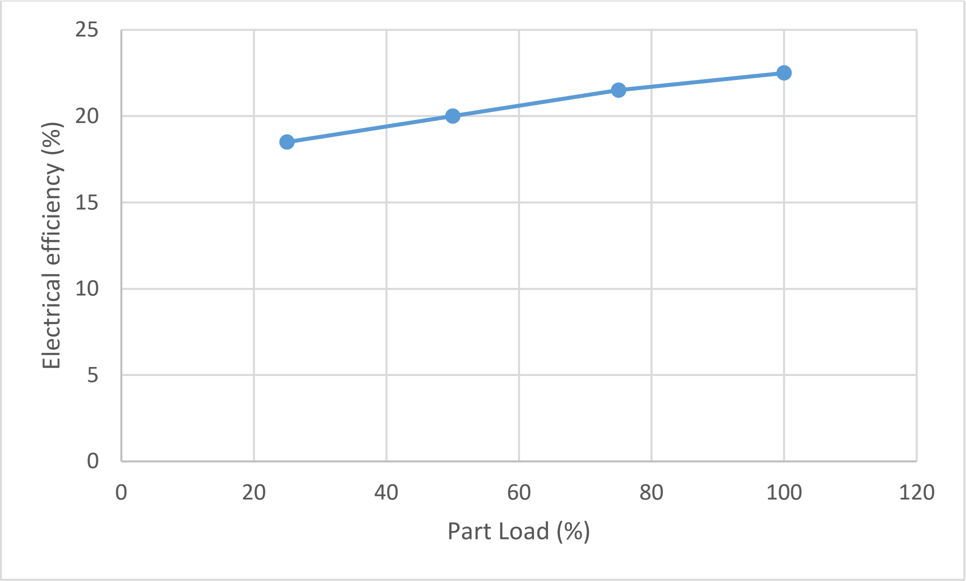


Figure 5-30: Variation of electrical efficiency with partial loading

Conclusion on modelling of the ICE: The modelled ICE compares favourably with the manufacturer's technical data. The model can be used by anybody to predict the performance or optimise any ICE. User only need to provide the following:

- Separately provide mass flow rate of combustion air and fuel. Alternatively, the air-fuel ratio can be provided.
- Input the temperature of combustion air.
- Provide the fractional composition of the fuel.

5.4.7 Validation and parametric studies of the absorption chiller

5.4.7.1 Validation of the chiller

The system is validated using mass and energy balance and comparison with experimental study on an absorption chiller Martínez et al., (2016).

In order to perform the mass balance analysis of the single effect absorption cycle, it is necessary that a "break" is introduced to provide input. This is included in the streams A and B (Figure 5.18). A well-articulated model will preserve energy within the cycle and thus result in similar mass flow rates on A and B. In the model, the stream entering the pump is named A while the one exiting the absorber is termed B. Table 5-26 compares entering streams with the stream leaving the system. As indicated in the Table, there is no mass loss within the system.

Table 5-26 Mass balance analysis of absorption cycle

MFR (kmol/hr)	Stream A	Stream B
Total	4.18585	4.18585
LiBr	1.78317	1.78317
Water	2.40268	2.83505

More so, considering the first law of thermodynamics, energy entering the system is expected to be similar to the energy exiting the system as illustrated in equation 5.42 (Somers et al., 2008).

$$E_{in} - E_{out} = 0 \qquad (5.42)$$

Where E_{in} and E_{out} symbolises inflow and outflow of energy into the system respectively.

Therefore, for a single effect system, modification of equation 5.42 gives equation 5.43:

$$[Q_{condenser} + Q_{absorber}] - [Q_{evaporator} + Q_{generator} + W_{pump}] = 0 \qquad (5.43)$$

Where $Q_{condenser}$ and $Q_{absorber}$ are the heat (kW) sink into the condenser and absorber respectively while $Q_{evaporator}$ and $Q_{generator}$ are the heat (kW) absorb by the chilling water and heat(kW) supply to the generator respectively. W_{pump} denotes the energy consumption of the pump in watt. Besides, the efficiency of the system called COP (Co-efficience of performance) is evaluated as the ratio of the evaporator duty to the generator duty. The result of the energy balance is shown in Figure 5-31.

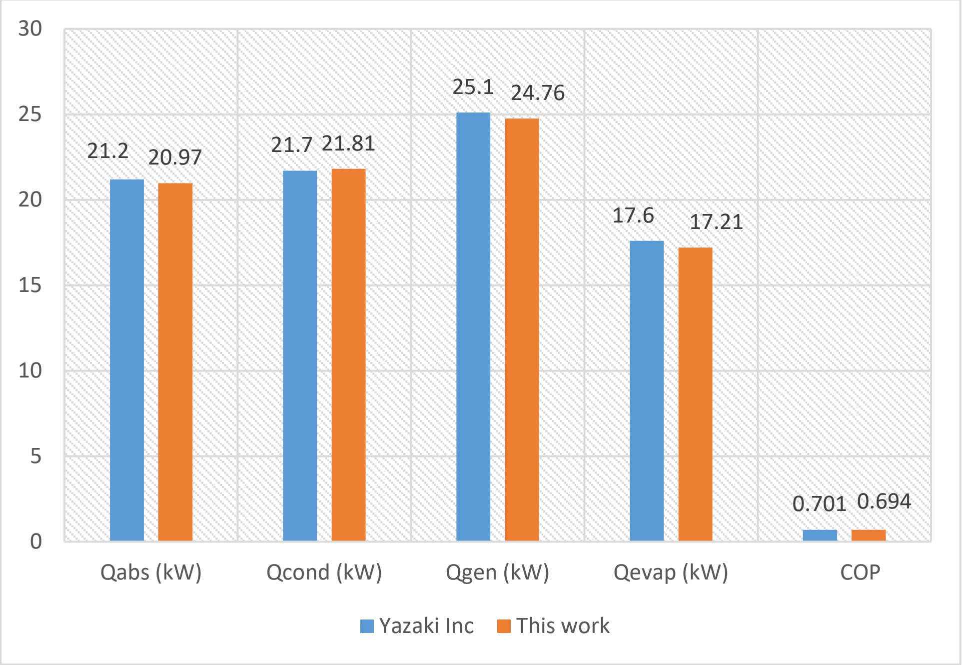


Figure 5-31: Comparison of simulation with experimental results

The energy flow within the system is nearly balanced save a difference of 0.38 W between inflow and outflow streams. This results in a slightly dissimilarity in the temperatures of streams A and B (Table 5.26). Consequently, there is a 2.40% deviation in temperature of stream entering the pump and the one exiting from absorber. However, the deviation is insignificant and does not affect the overall convergence of the system. Besides, such differences were also observed by (Darwish et al., 2008) and (Martínez et al., 2016) where overestimation of 4% and 7% were reported between experimental and simulation work. Besides, the predicted thermodynamic properties at different state points of the model is shown in the Appendix 6.

5.4.8 Parametric study on biogas cleaning unit

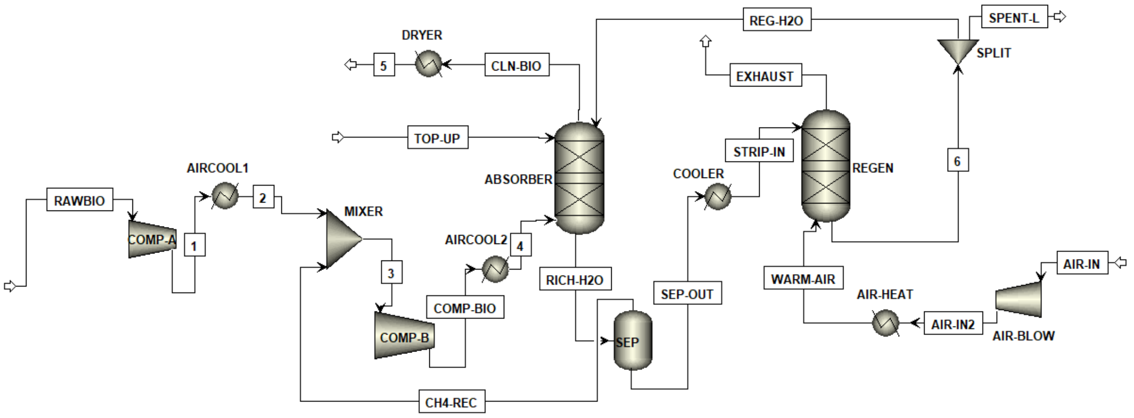


Figure 5-32:Aspen Plus model of the biogas water scrubber.

Flowsheet of the developed Aspen Plus is illustrated in the Figure 5.32 while the model's output as compared to (Cozma et al., 2013) and (Cozma et al., 2015) is indicated in the Table 5-27. As indicated on the table, the results from the model compares favourably well with the work reported in the literature. Having been satisfied with the model, a 70% methane purification and biogas-water ratio of 1: 2 (Magli et al., 2018; Nguyen et al., 2018) was imposed on the model to get the appropriate operational parameters.

Table 5-27: Comparison of simulation results with literature.

Particulars	Units	Cozma et al., 2013	This work
CO_2 RE	%	97.6	95.8
Methane loss	%	0.313	0.350
Treated flowrate	m^3/hr	303.36	303.36
Cleaned biogas			
CO_2	mole fraction	0.0093	0.0120
CH_4	“	0.967	0.963
H_2S	“	0.006 ppm	0.008 ppm
H2O	“	0.00228	0.0015

O2	“	0.0113	0.0115
N2		0.00976	0.0110
Stripper Exhaust			
CO_2	mole fraction	0.157	0.168
CH_4	“	0.000767	0.00843
H_2S	“	123 ppm	118 ppm
H_2O	“	0.022	0.026
O_2	“	0.171	0.182
N_2	“	0.647	0.615

5.4.8.1 Number of column stages

One of the factors that determins the CO_2 removal effeiciency (CO_2 RE) of absorption unit is the retention time between the participating fluids. This is commonly achieved through increased length of the absorption column. However, the higher the dimension of the column, the higher the initial capital and maintanance costs of the cleaning system. This consequently affect the unit cost of the cleaned biogas. Therefore, a compromise has to be made between the system efficiency and the required number of stages. As indicated in Figure 5-33, a CO_2 RE increases with increasing number of column stages. The increment is well pronounced as the number of stages increase from 2 to 6 after which it became less obvious. This trend is similar to the eralier studies reported on water absorption scrubbing (Cozma et al., 2015; Bashir, 2018; Ullah et al., 2017). About 93% CO_2 RE is obtained with 6 stages absorption column. Hence, a 6 stages absorption column with dimension 3 m height and 0.3 m in diameter is recommended. Importantly, removal of H_2S also follow the same trend but with recovery efficiency of around 65%.

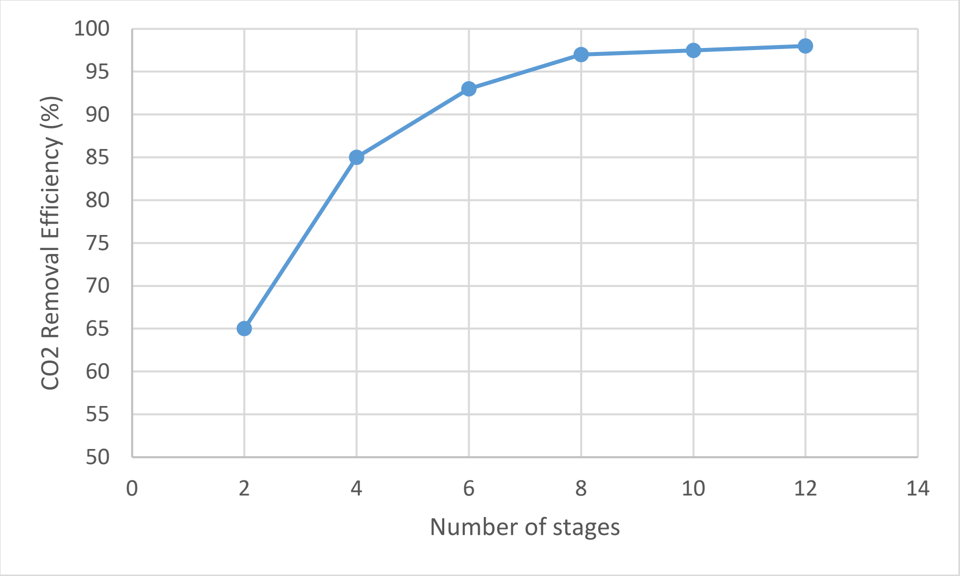


Figure 5-33: Varriation of CO_2 RE with the number of column stages.

5.4.8.2 Working pressure of absorber

Operational pressure is one of the factors that influence the effectiveness of absorption column. At constant liquid-gas ratio and column temperature, the rate of absorption is mainly influence by Henry's gas law such the dissolution rate is proportional gas partial pressure (Ullah et al., 2017). However, beyond a critical working pressure extra pressures do not lead to increased rate of absorption. Figure 5-34 Figure 5-34 indicates variations of both CO_2 RE and methane loss with working pressure. As the working pressure increases from 2-8 bars, CO_2 RE correspondingly increases from 60% to 97% but the increment is not significant after 8 bars. This is because at the solubility of CO_2 gas is enhanced at elevated column pressure. Besides, as the working pressure increases, methane loss reduces. This is because an increased working pressure favours dissolution of CO_2 in the washing liquid, increases methane content in the cleaned biogas. Hence, methane loss is reduced since there will be less methane concentration in the exhaust stream. More so, as the absorber temperature increases from 10°C to 30°C, CO_2 RE reduces from 99% to 88%. However, a 96% RE was obtained at 20°C and, considering the required energy, it is suggested that 20°C is a good compromise for the absorption system.

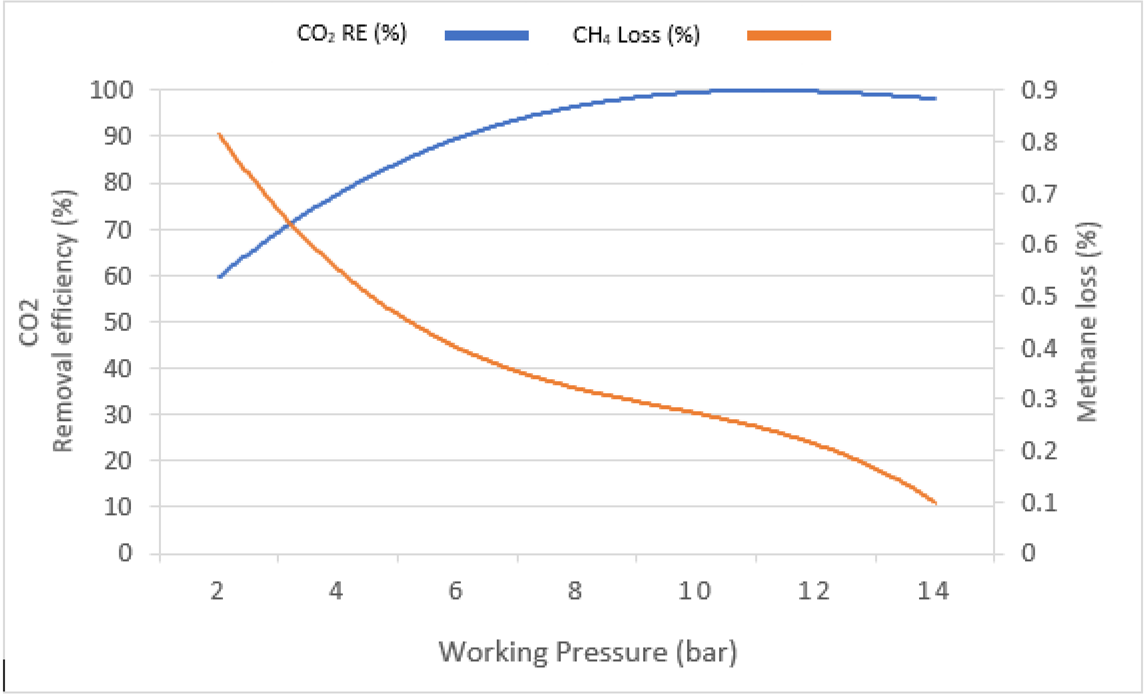


Figure 5-34: Effect of absorption pressure on methane loss of absorption efficiency.

Conclusion on modelling of the chiller: The modelled lithium bromide absorption chiller is not only properly converged but also compares favourably with experimental results. The model can be used by anybody to predict the performance of a similar single stage absorption chiller. User only need to provide the following:

- The duty of the generator or the available temperature of the heat source.
- The mass flow rate and fractional composition of the lithium bromide rich solution at the pump inlet.
- The temperature of the surrounding cooling air.

5.5 Conclusion of the chapter

The design configurations and materials selection for the CCHP has been presented. Five cylindrical fixed dome Chinese digesters of 1200m^3 each will require a total of 47.37 kW of heat to maintain mesophilic digestion of 194m^3/day of agricultural residue. Biogas obtained is cleaned in a 3.0 m by 0.3 m scrubber to obtain about 67% cleaned biogas which is used to power a 72 kWe engine from where heat is recovered to power a 3-ton absorption chiller and Atesta dryer. The result from this chapter also suggests that 48.9 tons/day of agricultural residue comprises of cattle market waste, cassava waste, cashew apple residue, maize stover and tomato residue can be technically collected from the study area. This can be anaerobically digested at 35^{0}C in five 1200m^3 digesters to produce a 4,666.32kg/day biogas containing 55% methane. The produced biogas is 1.5% in excess of what is required by the 420 rural households to meet their energy demand for lighting, cooling, drying and cooking as illustrated in Table 5-28. To do this, models of anaerobic digestion process, prime mover, absorption chiller and dryer has been developed in Aspen Plus and could be adapted by any user. Details of the required input to each of these devices has also been provided while output results of AP simulation of biogas and tri-generation system are presented in the Appendixes 7 and 8.

Table 5-28: Utilisation of biogas produced

Particulars	Quantity demanded (kg/day)
Fuel for the ICE	1170.24
Lost during biogas scrubbing	58.32
Cooking	948.75
Drying	2161.71
Pre-treatment	256.16
Excess	71.14
Total	4666.32

Chapter 6 : Techno-Economic Analysis

6.0 Introduction

In the preceding chapters, the system configuration was built and modelled while its operational viability was appraised in simulations. However, an overall understanding of the financial implications of the plant is required. This is because regardless of the high system's efficiency, a new project requires an assessment of the economic viability the essence of which is to help in the decision making such that a design with the acceptable performance can be selected. When the economic analysis tools are used at the early stage a project, an informed decision can be made by the decision makers on whether or not to proceed with a project (Short et al., 2005).

Therefore, in this chapter, an economic analysis of the plant is presented. Data from the Nigerian Electricity Regulatory Agency and other empirical studies from the literature together with the expected revenues would be used to analyse the economic viability of the system. As part of this analysis, this chapter would also look at the other costs and benefits that cannot be straightforwardly expressed through monetary value but can as well assist in the decision making.

Expectedly, prices and revenues uncertainties need to be accommodated. Therefore, a sensitivity analysis of the system will be performed to see how the economic indices change with some parameters.

6.1 Performing Economic Evaluation

To appraise the economic implications of a power system, it is pertinent to evaluate the investment implications of such system and how much would it generate in its lifetime. It can then be estimated whether this can be profitably provided, or an alternative would be required. This decision can be made with the use of some economic indices such as Discounted Payback Period (DPP), Internal Rate of Return (IRR), Net Present Value (NPV), Profitability Index and the Levelise Cost of Energy generation (LCOE). However, for a critical evaluation of these indices, indicators such as future investment and revenue, Capital costs, operation and maintenance costs etc. must be properly accounted for. Different scenarios are considered for the economic analysis which reflect needs of different categories of farmers:

I. A CHP system where electricity and drying system are the products.

II. A CHP system where electricity and cold storage are the products.
III. A tri-generation system where both drying and cold storage are the products.
IV. A poly-generation system involving the above with biogas for cooking.

6.1.1 Managing Future Investments and Revenues

When dealing with power project, it is obvious that both investment and revenue streams would occur regularly throughout the span of the project. For instance, while maintenance would be done regularly, collections of revenues is done monthly. Therefore, these time-dependent parameters must be accounted for in the analysis of project viability (Loeser et al., 2009). A period of 20 years and above is generally used for the evaluation of power plants (Castellanos et al., 2015;Patel et al., 2018). Though, most power plants are built to last more than 20 years since it takes long periods to recoup its high capital costs. Notwithstanding, uncertainties associated with long periods of forecasting clearly render longer periods increasingly questionable (Loeser et al., 2009). Hence, a period of 20 years will be adopted in this study. Generally, to evaluate the present values of both investment costs and future revenues the prevailing interest rates (ARUP, 2016) are usually adopted as illustrated in the equation 6.1

$$F_{cu} = \frac{F_{fu}}{(1+r)^n} \qquad 6.1$$

Where r is the annual interest rate (%) or discount value and n is the number of years between current and the future dates while F_{cu} and F_f are current and future values respectively. The salvage value of small power plants like this is considered infinitesimal to have a significant effect on the investment analysis. Thus, it is not considered. Besides, since all tradable commodities are affected by inflation rates (Loeser and Redfern, 2010) and commodity prices adjust to the inflation rates. For instance, if O&M costs is subjected to the inflation rates X%/annum, the selling prices of the plant products would have been subjected to a similar annual inflation rates. The effects of these differences on the cash-flow would be insignificant for a micro plant like the one being studied. Therefore, the effect of inflation rates on the plant is not considered.

6.1.2. Investments

Regardless of the plant size, the investments into power plant can be broadly divided into fixed and variable costs. These are further classified into capital cost, operation and maintenance cost and fuel cost (Loeser, 2010).

6.1.2.1 Capital cost

Capital cost are fixed cost spent at the beginning of a plant. However, the cost of replacements are often lumped with the capital costs but when this is done the discounted factor from when such replacement is done should be factored in (Short et al., 2005). The required capital costs are those for the purchase, transportation and installation of power system as highlighted by the Nigeria Electricity Regulatory Commission, (2015). Other capital costs are costs for the heat exchangers, dryers, chillers, cold storage and costs related to the organic fertiliser handling especially for sieving, pressing and bagging.

6.1.2.2 Operation and maintenance (O&M) costs

This includes cost of staffing and administration, purchase of consumables and spare parts. These costs are plant size-dependent and therefore classified as variable costs. For small power plants, O & M costs are very small compare to the capital cost. Hence, it is sometimes evaluated as a percentage of the capital cost (Towler and Sinnott, 2013).

6.1.2.3 Fuel cost

This is the cost that is acquired in bringing fuel to the generation site. In the case of biomass, it is the delivering cost of biomass at the site which include cultivation, processing and transportation costs for the purposely grown fuel crops, purchase with transport costs for purchased biomass. In some cases, biomass is obtained freely and only transportation and logistics costs are accounted for. In some community-based power plants within rural areas, biomass is sometimes swapped with biogas for domestic cooking. This possibility would also be explored to assess the impacts of the fuel costs on the plant’s viability. Details of the data used for the economic analysis is presented in the Table 6-1.

Table 6-1: Parameters for the economic analysis

Parameter	Unit	Amount	Source
Capital cost (ICE & AD unit)	$/kW	2900	NERC-Nigeria Electricity Regulation Commission (2015)
Fixed O&M (ICE & AD unit)	USD/kW/yr.	53.50	“
Variable O&M (ICE & AD unit)	USD/MWh	0.95	“
Fuel cost	USD/MWh	5	“
Parasitic load	%	10%	“
Electricity price (rural) ($·MWh -1)	USD/MWh	13.11	“
Electricity price (poor urban households)	USD/MWh	89	“

REA proposed average price	USD/MWh	420	“
Electricity prices (considered)	USD/MWh	50	Considered
Price yam tuber (local)	USD/yam	0.82	Local market
Price yam tuber (foreign)	USD/yam	2.43	Online
HQCF	USD/kg	0.25	Local market
Cassava (sundried)	USD/kg	0.12	Local market
Tomato Dried	USD/kg	2.27	Local market
Tomato cold (normal)	USD/kg	0.21	Local market
Tomato cold (crashed)	USD/kg	0.07	Local market
Cooking gas	USD/MJ	1.31	Local market
Grain (maize)	USD/kg	1.12	Local market
Organic fertilizer	USD/kg	0.90	Local market
Quantity processed (HQCF)	Tonnes/year	20.35	AP model
Quantity processed (yam)	tubers/year	1200	AP model
Quantity processed (maize)	Tonnes/year	2.313	AP model
Quantity processed (tomato)	Tonnes/year	3.75	AP model
Quantity processed (manure)	Tonnes/year	913.40	AP model
Life Span	year	20	Castellanos et al. (2015)
Interest rates	%	7,9,20	Online
Capacity	kWe	72	Caterpillar Inc. (2011)
Availability	%	90	“
Dryer (capacity)	kg/cycle	100	Boroze et al. (2014)
Dryer capital cost	USD	3515.78	“
Dryer O& M cost	USD/year	250	“
Chiller capital cost	USD	11,836.1	Local market
Chiller O&M cost	USD/MWh	15	Local market

6.1.2.4 Revenues.

The revenues are obtained from the sales of plant’s products: electricity, cold stored and dried produce and organic fertiliser. As stated earlier, a power plant less than or equal to 100 kWe falls under regulation of the Nigerian Rural Electrification Agency (Rural Electrification Agency), 2015). At the moment, there are about 14 GW self-generated small petrol and diesel gen-sets costing between USD0.25 to USD0.75/kWh. Besides, there are currently over 85 million rural and semi urban Nigerian spending approximately USD1.5/week on mobile phone charging, torches, kerosene lamps ((Rural Electrification Agency, 2017b). Thus, the REA is using a market-based approach to fix electricity tariffs payable on the stand alone mini-grid power plants. Using this approach, the internal rate of return (IRR) is capped at

15% to determine the appropriate tariffs payable by the consumers. With this approach, the electricity prices of some case studies varies between USD0.33/kWh to 0.51/kWh depending on the plants size (Rural Electrification Agency, 2017a). The average electricity price of these case studies is USD0.42/kWh. This is thus used as the base price for the REA. However, this price is considered too much for the farmers. Therefore, other prices examined are USD0.013/kWh; USD0.089/kWh and USD0.05/kWh with the first two being the current tariffs of grid connected rural and poor urban households while the last is considered reasonable enough for rural settings.

Agricultural products: cassava, maize and tomato are selected for the analysis. From the survey, the crops represent the predominantly grown crops that requires drying and cold storage.

Cassava is primarily processed into cassava flour which is obtained by sun-drying of cassava cake. Income from drying is calculated as the difference in the price of High-Quality Cassava Flour (HQCF) obtained from industrial drying of cassava cake and price of sundried cassava flour (SCF). The prices are gotten from the Nigerian local markets. As at the time of this survey, HQCF cassava is sold for USD0.25/kg while SCF was sold for USD0.12/kg. Hence, annual income from drying is taken as a product of this difference and the quantity of cassava floor processed per annum.

Maize is predominantly staple food and there is not much difference in price disparity between sundried and industrial dried shelled maize. However, there exists quality standard for its industrial supply especially moisture content and presence of foreign materials. Hence, processed maize is assumed to be supplied for industrial use and the price is applied.

Agricultural activities in Nigeria typified what is obtainable in most SSA countries where cultivation is predominantly rain fed. Thus, cold storage is not only used to prolong the shelf-life of the products but also controls influx of farming produce during harvesting period when supply always exceeds demand. In this study, cold room is assumed to be used for the storage of tomato only. Thus, income from cold storage is taken as different between the normal selling price and price of tomato when price is crashed due to oversupply. For instance, during the field work, a 15 kg basket of tomato at the local market (Oja Oba) was sold for #1,800 (£3.82) in July 2017 and later dropped to #500 (£1.06) by first week in September 2017. More so, the price of organic fertiliser is obtained from the local suppliers.

A part of the biogas produced is evaluated for cooking. At the moment, the predominantly used cooking gas in Nigeria is the Liquefied Natural Gas (LNG) filled in cylindrical cans and vary from 5kg to 25kg with the average refilling price of #431.2/kg. Hence, the refilling price of biogas is estimated from the energy content of LNG using 46.1MJ/kg and 22.5MJ/kg as the energy content of LNG and biogas respectively. Besides, a situation where farmers exchange cooking gas for biomass was also evaluated.

The local price of organic fertilizer is around #5500 (USD18) per 20 Kg with the moisture content vary between 10 and 15%. The produced manure is expected to be sold as pulverised cake having 40% moisture content. This reduces the bulkiness and challenges of carrying liquid fertilizer while also make the nutrients easily available for immediate use of the plants (Sutton et al., 1986).

6.1.3 Economic Indices

Using the above investment costs and revenues, the economic indices considered are the Net present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Periods (DPB) and the Levelised cost of energy (LCOE) as these are considered enough tools to make informed decision on the investments.

The NPV (equation 6.2) compares the future returns on investment with the current value of the investment cost and defined as (Short et al., 2005):

$$\text{NPV} = \sum_{n=0}^{N} \frac{Fn}{(1+d)^n} = F_0 + \frac{F_1}{(1+d)^1} + \frac{F_2}{(1+d)^2} + \cdots + \frac{F_N}{(1+d)^N} \qquad (6.2)$$

Where NPV is the net present value, Fn is the net cash flow (US$) in year n; n is the analysis period while d is the annual discount rates.

The IRR is the rates that sets NPV of cash flow at zero as shown in equation 6.3 (Short et al., 2005).

$$NPV = 0 = \sum_{n=0}^{N} \frac{F_n}{(1+IRR)^n} \qquad (6.3)$$

Where NPV, F_n, d, and n are as defined above.

LCOE represents the break-even price (P_e) of electricity. It is the lifetime cost of unit energy generation expressed in the present value (Ouyang and Lin, 2014) as presented in equation

6.4.

$$LCOE = P_e = \frac{\sum_{n=0}^{N} \frac{(I_n + O_n + M_n)}{(1+r)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+r)^n}} \quad (6.4)$$

Where, O_n, M_n, E_n and r represent the initial investment cost in year n, operation cost in year n, maintenance cost in year n, electricity production in year n and discount rate respectively

Discounted Payback period (DPP) is calculated from the discounted cash inflow:

DCI

$$DCI = \frac{Real\ cash\ inflow}{(1+r)^n} \quad (6.5)$$

Where DCI is the discounted cash inflow (UD$), r is the discount rate while n is the analysis year.

$$DPP = A_{\mathrm{DCI}} + \frac{B_{\mathrm{DCI}}}{C_{\mathrm{DCI}}} \quad (6.6)$$

Where

A is the last period with negative cumulative DCI

B is the absolute value of cumulative DCI at the end of period A;

C represents DCI during the period after A.

Profitability Index (PI) calculates the ratio between the present value of the future cash flow and capital cost of an investment. An investor would proceed with a project if PI is greater than 1 while PI less than one suggests the investment should be discontinued.

$$PI = \frac{NPV}{I_{inv}} \quad (6.7)$$

Where I_{inv} is the initial costs of the investment.

6.2 Results and discussion

6.2.1 Techno economic analysis of CHP system for electricity and drying of agricultural products

In this scenario, the 72kWe biogas driven ICE supplies electricity to the village. The recovered heat from the water-cooling jacket is used to maintain the mesophilic anaerobic digestion of the farm residue while the recovered heat from the exhaust is used to power the Atesta dryers. The effectiveness of heat exchangers for the drying unit and anaerobic digestion process is taken as 0.67 (Somers et al., 2008). The system is assumed for the drying of aforesaid agricultural products. A 90% system availability was assumed while economic analysis is done using the values presented in Table 6-1. The electrical and CHP efficiencies of the system are as defined in the equations 6.7 and 6.8 (Khan et al., 2014); (Lamidi et al., 2019b):

$$\mu_{elc} = \frac{W}{m_{biogas} x LHV_{biogas}} \text{ X } 100 \qquad (6.7)$$

$$\mu_{chp} = \frac{W + Q_{dry} + Q_d}{M_{biogas} \cdot LHV_{biogas}} X\ 100 \qquad (6.8)$$

where W is the electricity production by the CHP in kJ.h^{-1}; Q_{dry} is the duty of the dryer (kJ.h^{-1}); Q_d is the heat supply to the anaerobic digestion system in kJh^{-1}; M_{biogas} is the fuel consumption rate of the ICE in m^{3}h^{-1} while LHV_{biogas} is the lower heating value of biogas in kJm^{-3}; μ_{ele} and μ_{all} are the electrical and overall efficiency respectively.

The result from the Aspen Plus modelling of the unit indicates that at 90% availability, the system is able to produce 1555.2 kWh/d of electricity while the recoverable heat from the exhaust and cooling units are 1424 .49 kWh/d and 2816.59 kWh/d respectively. The recovering of heat for drying and AD process increases the efficiency of the system to 68.4% which represents a significant improvement compare to the electricity generation only which has an efficiency of 26.73%.

The results of the economic analysis indicate that the profitability of the system is largely driven by the price of electricity. Income from the drying of agricultural produce depends on the type and the nature of the crops processed. i.e whether the dryer is used for the drying of cash crops like cocoa and cassava chips or food crops like grains or tomato. Hence, considering the former electricity tariff system where villagers paid USD0.013/kWh of electricity, the system is not profitable regardless of the banks' lending rate as all economic indices are negative. This is because being farm based, such systems are entitled to the loan from the Nigerian Agricultural Development Bank, Bank of Industry and Commercial banks with the interest rates 7%, 9% and 20% respectively. At these interest rates, the Levelized Cost of Energy are $0.082, $0.090 and $0.141/kWh respectively. Hence, electricity price below 0.082/kWh remains uneconomical except if generated income from sales of agricultural products can offset the differences.

Sales of electricity contribute about 31.43% to the income generation while contributions from processed crops varies between 34% to 68.75 depending on the prices of the products. At the electricity tariffs detailed in the section 6.1.2.4, the PI is as indicated in the Figure 6-1.

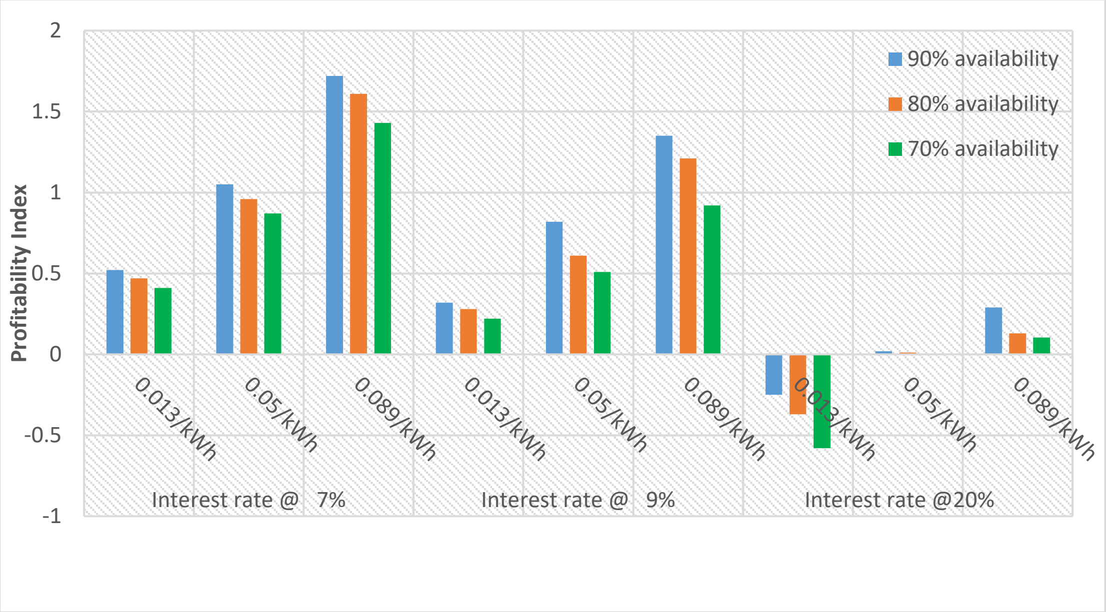


Figure 6-1: Effects of price change and availability on profitability index

Figure 6-1 indicates that both prices of electricity and availability have a significant influence on the profitability of the system. At 90% availability and 7% interest rate, as the electricity prices increases from 0.013/kWh to 0.089/kWh, profitability index also increases from 0.52 to 1.72. The figure also shows that the commercial banks' lending rates is not feasible for this kind of project. At the lending rates of 7% and 9%, the payback periods equally changes significantly depending on the selling prices of electricity as shown in the Figure 6-2. However, if 15% internal rates of return is used as yardstick as envisaged by the Nigerian Rural Electrification agency, electricity price of USD0.013/kWh would be designated unfit since the Payback period at this price would have been more than 6-7 years. Electricity tariffs of USD0.05/kWh and 0.089/kWh both have Discounted Payback Period (DPP) less than 6 years but USD0.05/kWh may be considered more suitable for the rural dwellers without stressing them unnecessarily.

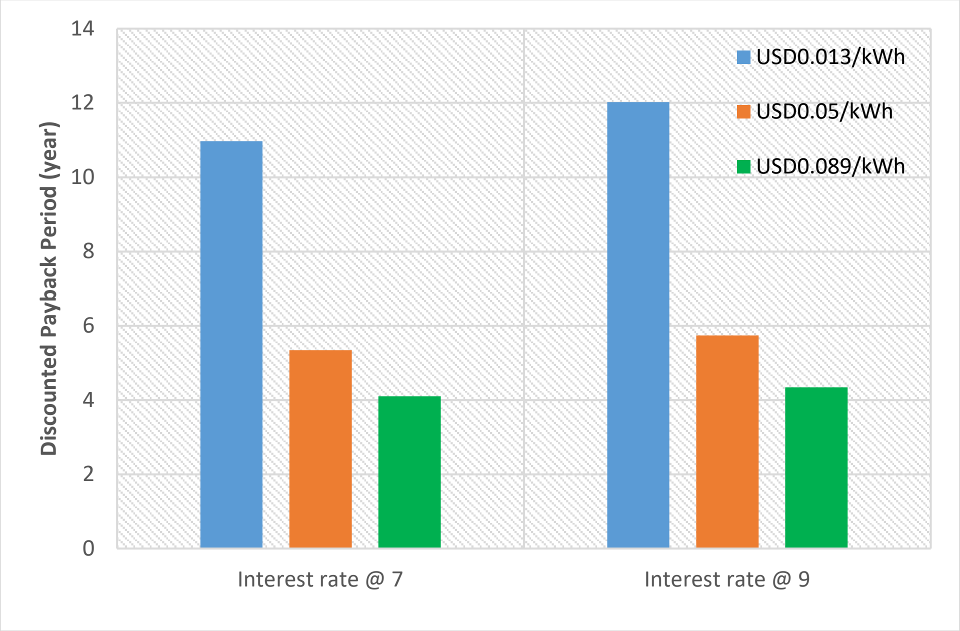


Figure 6-2: Variations of payback periods with interest rates

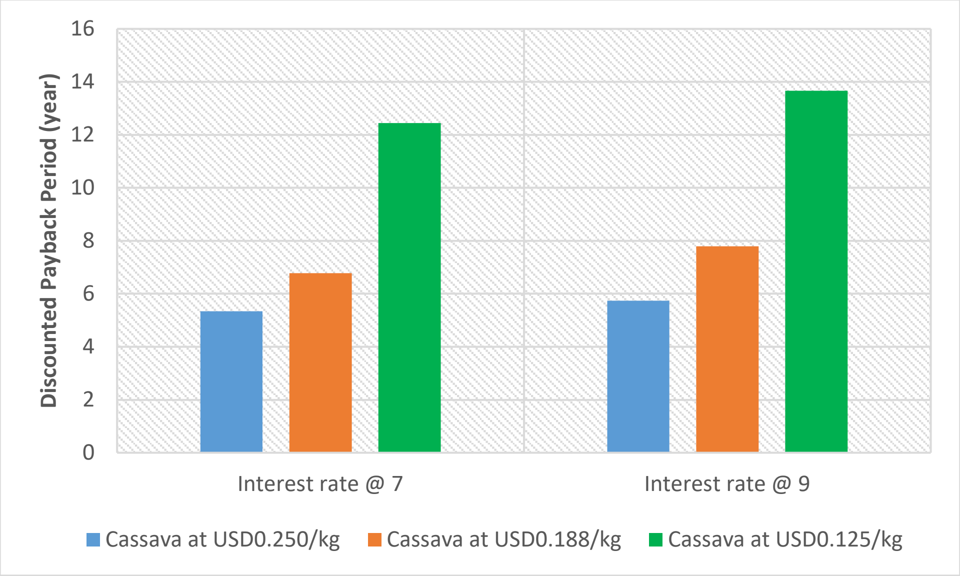


Figure 6-3: Changing prices of HQCF on DPP

Meanwhile, at this electricity price, the viability of the system largely depends on the market price of agricultural prices as illustrated in Figure 6-3 with the varying prices of HQCF. As indicated in the figure, the system becomes uneconomical when the price of HQCF reduces beyond 25%. Details of this cogeneration system is presented in Lamidi et al., (2017b)

6.2.2 Techno economic analysis of CHP system for electricity and cold storage of agricultural products

In this case study, agricultural residue is conditioned and anaerobically digested at 35^{0}C. It is then enriched using water scrubbing and the biogas is subsequently used to power an internal combustion engine (ICE). Heat from cooling jacket of the engine is recovered to partly maintain AD process and to drive absorption chiller. Heat from cooling jacket of the engine is recovered to partly maintain AD process and to drive absorption chiller. The heat from exhaust is recovered to power three more absorption chillers with rated cooling power of 17 kW. Chilled water produced from evaporator is used to maintain the temperature of the yam cold storage measuring 6 m×5 m×2 m with 1 m peak for the roofing. It is made up of wood pine, corkboard and concrete as inner layer, insulator and outer layer respectively. The system is as indicated in the Figure.

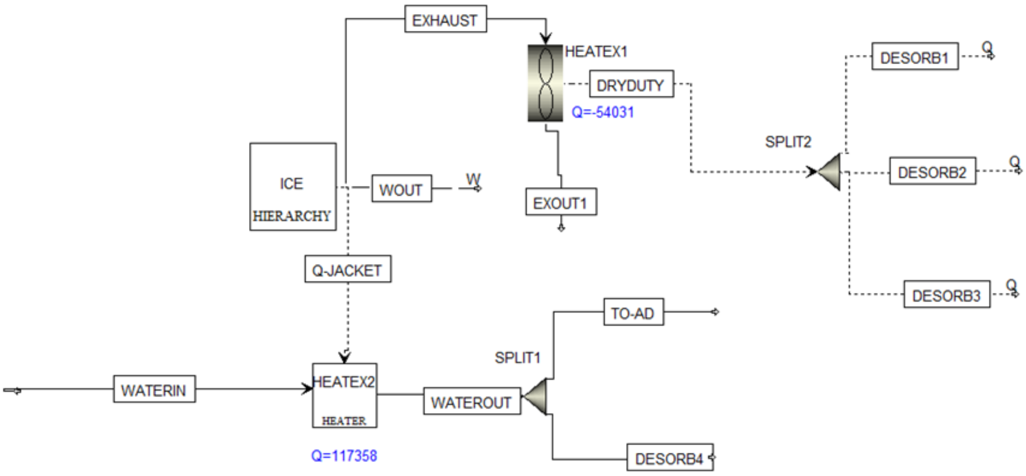


Figure 6-4: AP model of ICE and heat recovery for cooling.

Input for the economic analysis is as indicated in Table 6-1 but the price of cold storage is obtained from the local suppliers while income from electricity and cold storage is as detailed in the section 6.1.2.4. The system is assumed for the storage of yam tubers and tomato with yam tuber having potential of being sold in the local market or export while tomato is consumed locally. So, the economic analysis was performed with this market views.

Heat balance associated with microbial activities as detailed in the section 5.1.1.1 is presented in Table 6-2. The signs show whether heat is added (+) or generated (-) indicating endothermic and exothermic processes respectively. From the Table, it is indicated that the entire process is exothermically producing heat of about 16.26 kW. The total heat requirement for digestion process is indicated in Table 6-3. It is indicated that substrate warming up contributes the largest heat demand. From the simulation results, about 117.4 kW heat can be recovered from cooling water jacket. This produces 1550 kg·h^{-1} of water at 85°C in which 47.5 kW is used for AD process.

Table 6-2: Biochemical energy balance of AD system

Composition	Percentage (dry basis)	Molar mass	Daily flow (kg·day^{-1})	ΔH_R^0 (kJ·mole^{-}	Enthalpy heat (KW)
Carbohydrates	64.44	180	3466.87	-138.50	-30.87
Protein	7.00	89	376.6	+198.50	+9.72

Lipids	4.33	300	232.95	+544.50	+4.89
Total heat of enthalpy					**-16.26**

Table 6-3: Total heat load of AD process.

Required load (kW)	Mesophilic (35^{0}C)
Substrate warming up	+62.72
Biochemical heat of reaction	-16.26
Heat loss through insulation	+0.88
Heat loss by radiation	+0.0386
Total heat load required	**47.38**

The required cooling load as illustrated in Table 6-4 is 35.50 kW. The highest cooling load requirement is the sensible cooling, which is required to cool the tubers from atmospheric temperature to the 15^{o}C storage temperature. To maintain this storage temperature, heat generation through respiration is carried away while the system’s heat loss should be accordingly compensated. The design of system must provide this cooling load. Exhaust heat is only able to power three 17 kW LiBr absorption chillers shown in **Error! Reference source not found.**. Three chillers produce 26.23 kW cooling power. The remaining 9.27 kW cooling power is obtained from a 25kW single stage LiBr absorption chillers with a reduced coefficient of performance of 0.4.

Table 6-4: Cooling load requirement.

Particulars	Required load (kW)
Sensible cooling load required	34.83
Respiratory heat generated	7.43×10^{-2}
Heat loss through insulation	5.93×10^{-1}
Heat loss by radiation	1.43×10^{-3}
Total cooling load required	**35.50**

The effects of interest rates on the LCOE is illustrated in the Table 7.5 where LCOE varies correspondingly with the increasing lending rates. Hence, as earlier noted, for the system to be feasible, the selling price of electricity should, at 7% interest rates, be above

USD0.082/kWh except if the additional income generated from the sales of agricultural products processed is enough to balance the differences.

Table 6-5: Changing of LCOE with interest rates

Interest rates (%)	Levelised cost of electricity (USD)
7	0.082
9	0.088
20	0.123

The system is both influenced by the price of electricity and other processed commodities. Therefore, variations the Net Present Values (NPV) with changing prices stored yam is presented in Figure 6-5.

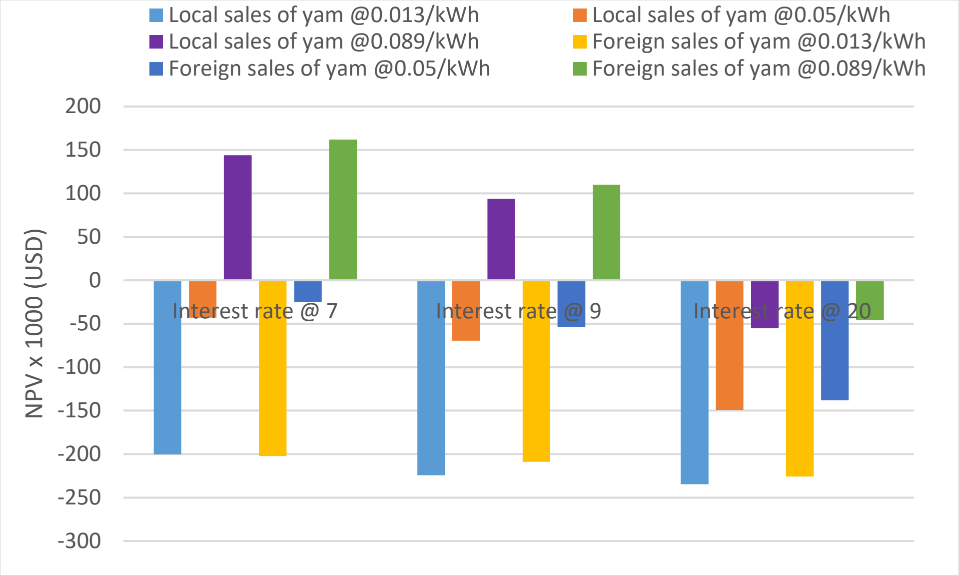


Figure 6-5: Variations of NPV with interest rates

It is observed that the system is only profitable when electricity is sold at USD0.089/kWh while even income from the foreign sales of the yam tuber is insignificant to make the NPV positive at neither USD0.013/kWh nor USD0.05/kWh. Even at USD0.089/kWh, the DPP is 7.13 years which could be considered as red zone. This is because any slight reductions in the price of yam tubers will have negative impacts on the economy of the system. Notwithstanding, the economic performance of the system is better when used for the cold storage of tomato as indicated in Figure 6-6. When tomato is substituted for yam tubers; the

DPP reduces by 12.2% from 7.13 years to 6.26 years. The conference paper (Lamidi et al., 2017a) was based on this scenario the content of which has been modified and presented in Lamidi et al., (2019).

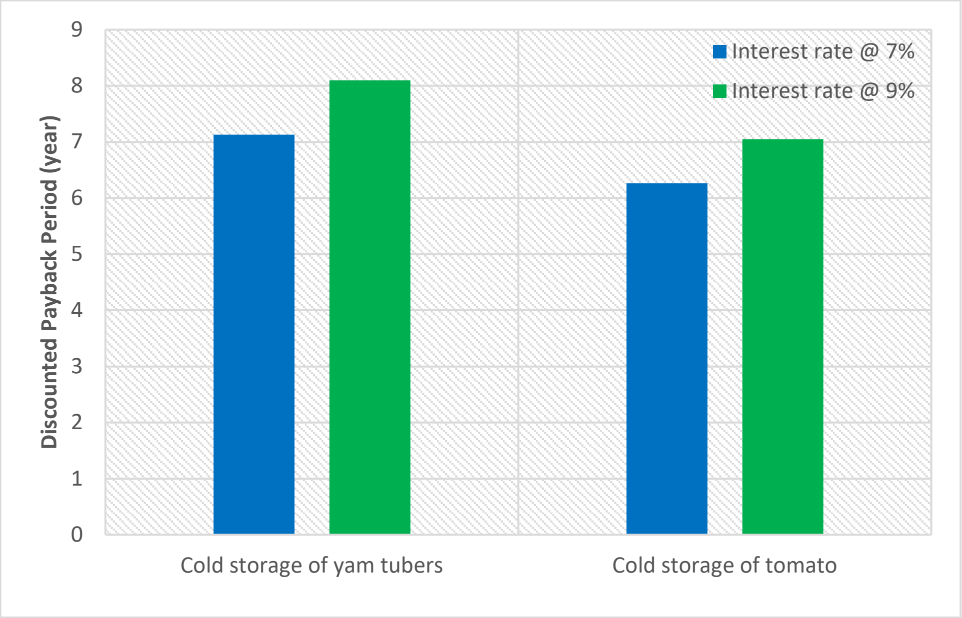


Figure 6-6: Effects of agricultural products handled on payback period.

6.2.3 Techno economic analysis of Tri-generation system for drying and cold storage of agricultural products

The CCHP system is made up of a 72 kWe CAT engine, heat recovery; cold storage and drying units as illustrated in the Figure 6-7. The system is assumed for the cold storage tomato while tomato, grains and high-quality cassava flour (HQCF) are dried. In addition to the electrical efficiency defined in the equation 6.7; the overall efficiency of the CCHP is as defined in the equation (Al-Shemmeri, 2011;Lamidi et al., 2019b)

$$\mu_{all} = \frac{E_{ele} + Q_{cs} + Q_{dry} + Q_{AD}}{M_{biogas}.LHV_{biogas}} X\ 100 \qquad (6.9)$$

where E_{ele} is the electricity production by the CCHP in kJh^{-1}; Q_c is the cold storage duty in kJh^{-1}; Q_{dry} is the duty of the dryer (kJh^{-1}); Q_{AD} is the heat supply to the anaerobic digestion system in kJh^{-1}; M_{biogas} is the fuel consumption rate of the ICE in kgh^{-1} while LHV_{biogas} is the lower heating value of biogas in kJm^{-3}; μ_{ele} and μ_{all} are the electrical and overall efficiency respectively. Input for the economic analysis and revenues are as discussed earlier.

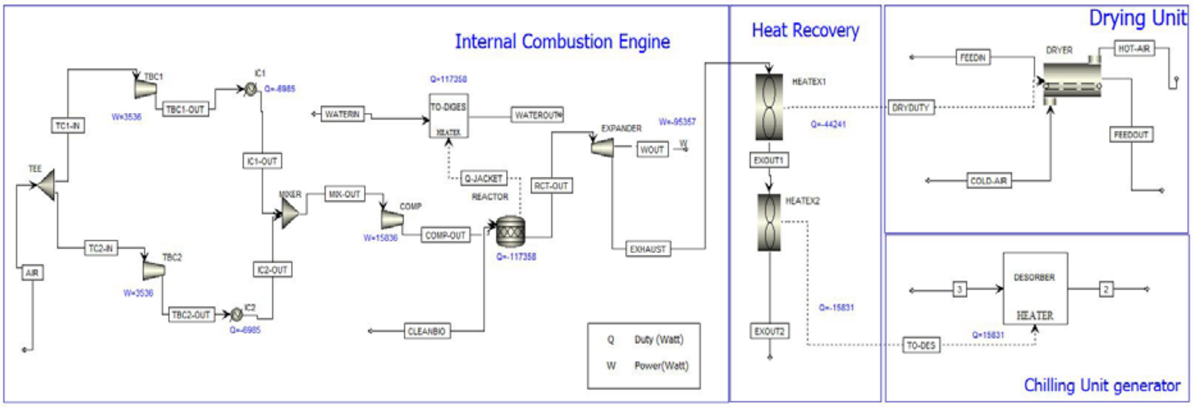


Figure 6-7: Aspen Plus simulation of AD and cleaning process.

The electrical efficiency of the system is 26.73%. The use of tri-generation increases the system's overall efficiency to 71.5%. The dryer can dry 2264 kg.day^{-1} of cassava flour cake yielding 1584.8 kg.day^{-1} of HQCF while 555.33 kg.day^{-1} of tomato is cold stored.

The LCOE as observed in Figure 6-8 is very sensitive to box discount rates and availability. LCOE increases with the increasing lending rates. Thus, at 70% availability, the electricity must be sold above USD0.104/kWh for the system to be economical. The profitability of the system is also significantly influenced by the type of crops processed as illustrated in Figure 6-9. For example, at 9% lending rate, the profitability index reduces by 23.73% when the system was used for drying of maize which is a staple food against HQCF which is an industrial product as well as staple food. At USD0.05/kWh and 7% interest rate, when cold storage of tomato is combined with either drying of HQCF, tomato or maize the DPP are 2.5 years; 3.6 years and 4.7 years respectively. Importantly, as the prices of electricity reduces, revenues from the processing of agricultural products increasingly have influence on the payback period. Detail of this scenario can be found at (Lamidi et al., 2019b).

Figure 6-8: Variations of LCOE with discount rates and availability

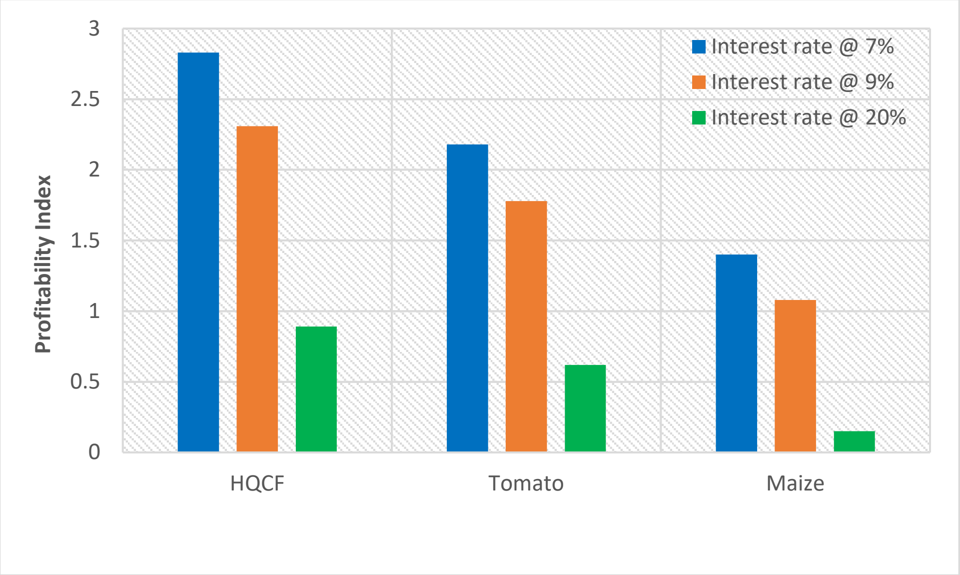


Figure 6-9: Effects of agricultural products processed on viability

6.2.4 Techno economic analysis of poly-generation system for cooking, organic fertiliser and processing of agricultural products

In this system, in addition to the features of tri-generation presented above, both organic manure and cooking gas are produced and sold. The cost for the processing of the organic manure which involves settling tank, screening, dewatering and pulverising equipment is assumed 10% of the total capital cost. An extra 10% of the electricity generated is assumed to be utilised at the manure processing unit (Huiru et al., 2018) thereby making the autoconsumption of the plant 20% of the electricity generated. The prices of organic fertiliser and biogas were obtained from the local markets. For the biogas, the price is calculated from the current price of the liquefied petroleum gas (LPG) using differences in the calorific values. LPG which has the calorific value of 46.1MJ/kg is currently being sold at USD1.31/kg at the local market (Kumar, 2018). Thus, the cost of energy is USD0.0284/MJ. Two approaches are used for the economic evaluation are: 1) that the biogas is exchanged for biomass for farmers; 2) that the biogas is sold to the farmers why biomass is purchased at USD4/MWh as stipulated by the Nigerian government.

6.2.4.1 Poly-generation without payment for biogas

The effect of varying interest rates on the economic indices is presented in theTable 6-6. The NPV of the plant are positive at 7 and 9% interest rate but will be negative at the lending rates of the commercial bank. Values for the profitability index and payback period have similar trends indicating that obtaining loan from the Nigerian commercial banks for such project is not feasible. The payback periods of 6.5 years obtained with the lending rates of 7 % looks good and comparable to the conventional below 7 years (Carbon Trust, 2012) threshold being used for the renewable energy technologies. This threshold is exceeded if 9% interest rate is considered while interest rate of 20% do not make any economic sense. However, these payback periods may be acceptable if other non-monetary benefits of the plant are considered.

Table 6-6: Variation of the economic indices with interest rate @ USD0.05/kWh

Interest rate (%)	NPV	Profitability index	Payback period
7	596,288	0.94	6.53
9	410,047	0.67	7.76
20	-53,467	-0.09	Negative

The LCOE are USD0.261kWh^{-1}; USD0.280kWh^{-1} and USD0.394kWh^{-1} for 7%, 9% and 20% interest rate respectively. This indicate that electricity must be sold above these prices for the system to be feasible or other incomes generated from the system must be able to offset the shortfall. From the aforesaid LCOE, if electricity is sold at USD0.05/kWh, at 7% interest rate electricity would have contributed only 21% to the income generation. Hence, the profitability of the system is more driven by the prices of commodities processed. As illustrated inFigure 6-10, at 7% interest rate, the payback of the system increases from 3.97

years to 8.85 years when used for the drying of HQCF with tomato storage and drying of grains with yam storage. This suggests that the system is better when used for the processing of both staple foods and industrial products rather than handling of staple foods only.

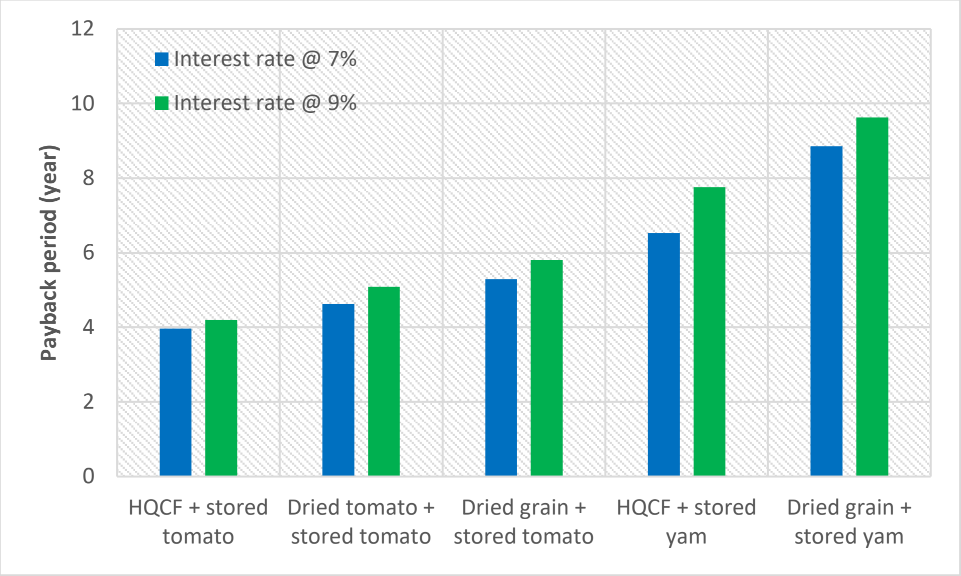


Figure 6-10: Variations of payback period with the products processed

6.2.4.2 Poly-generation with payment for biogas

The economic performance of the system is indicated in the Table 6-7. It can be seen that rather than the trade by batter system paying for the biogas significantly improves the economy of the system with all economic indices showing positive. However, similar to the above observation, rather than the electricity prices, the economic indices are strongly influenced by the prices of other products such as cooking gas, organic manure and agricultural products handled. Prices of fossil fuel is known to influence viability of renewable energy projects (Bridle and Kitson, 2014;Shah et al., 2017). In the case of Nigeria, government is trying to encourage people to shift from the use fuelwood and kerosene to a more sustainable cooking gas.

Table 6-7: Effects of interest rate on the economic indices at USD0.05/kWh

Interest rate (%)	NPV	Profitability index	Payback period
7	905,385	1.50	4.89
9	699,652	1.16	5.22
20	101021	0.17	9.86

Nigeria, being oil producing country, it is envisaged that government might introduce policies in the form of subsidies that may lead to the reduction of the prices of cooking gas. Hence, while all other variables are kept constant while assuming that the system is used for drying of HQCF and yam storage, the prices of cooking gas is reduced by 25, 50 and 75% respectively. The effect of the reduction is illustrated in Figure 6-11where at 7% interest rate, the payback period increases from 4.89 years to 8.42 years.

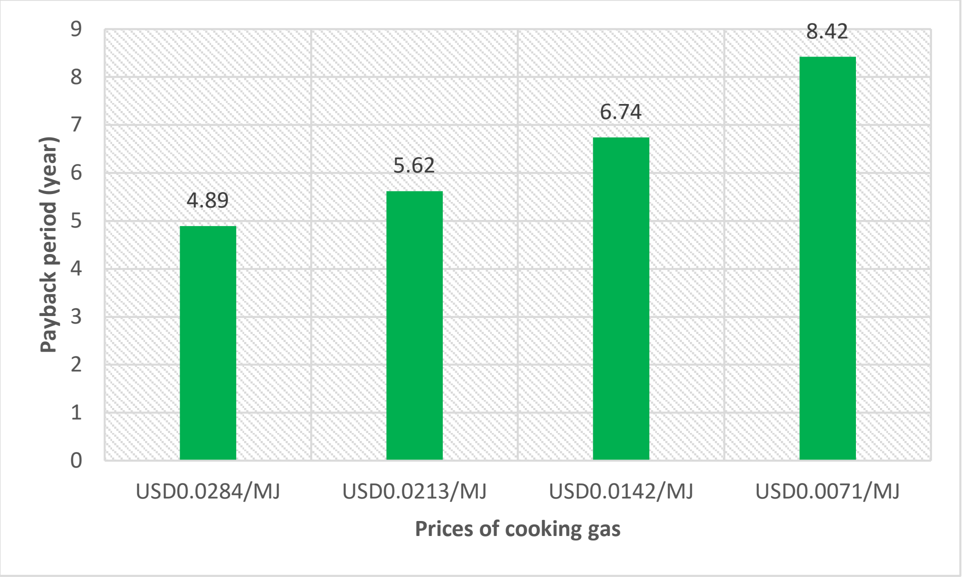


Figure 6-11: Effects of varying prices of cooking gas on payback period

6.3 Conclusion

The use of CHP increases the efficiency of the system from 26.73% to about 75%.

Rural Electrification Agency's price of USD 0.420·kWh^{-1} looks good with the discounted payback period within less than 4 years for electricity generation only. However, this is considered too much since it put unnecessary burden of electricity tariff payments on already impoverished farmers, majority of whom currently lives with less than USD2 per day. This burden could be reduced by combined generation systems where heat is recovered for processing of agricultural products such that the extra income generated can be used to compensate some of the differences. The system is not economically viable at electricity tariffs of USD0.013/kWh currently charged for the rural grid connected consumers as the discounted payback period is rather too long. More so, the cogeneration system where heat is recovered for either cold storage or drying has a discounted payback period ranging between 4-12 years at 7% interest rate provided the electricity is sold at USD0.089/kWh. However, it is very susceptible to the price volatility of agricultural products. At USD0.089/kWh, tri-generation system has a payback period of 2.5 years which increases to 4.7 years when electricity is sold at USD0.05/kWh. However, the poly-generation system is viable at USD0.05/kWh which is 43.8% lower than the USD0.089/kWh being paid by the poor urban households. At the USD0.05/kWh, income from processing of agricultural products plays significant roles in the economy of the system. However, this role is influenced by the type and nature of the agricultural products processed. For the poly-generation system, though the payback period appears more mouth-watering when farmers pay for biogas while biomass is purchased; yet it is possible to operate the system with swapping of biomass for biogas. When biomass is swapped, the system is better operated with processing of both staple and industrial agricultural products.

Chapter 7 : Conclusion

7.1 Introduction

This thesis has offered an in-depth study into finding a solution to the energy poverty and heavy post-harvest lost within rural communities in Nigeria which is also applicable to the rural areas of the Sub-Saharan African region. The study particularly set out to, using locally available biomass resources, synchronises energy delivery with basic processing of agricultural products using biogas driven tri-generation system.

The specific objectives are to:

i. Investigate the current energy usage and demand of the farming households in a selected Nigerian rural community;
ii. Identify the main agricultural products produced from the community; and the level of post-harvest losses in the area;
iii. Identify and investigate the renewable energy resources (agricultural biomass residue) available in the area; carry out a field study and collet the typical wastes samples;
iv. Analysis of the typical wastes samples to identify the appropriate energy recovery option;
v. Design a biogas driven CCHP system that can satisfy the required energy demand;
vi. Set up computational models of the poly-generation system including: an anaerobic digestion model for production of biogas; a CCHP system for providing drying, heating, cooling and power using Aspen Plus simulation tool.
vii. Perform economic evaluation of the system.

7.2 Key findings of the study

In accordance with the GREEN VILLAGE INITIATIVES of the Nigerian government in context of which this scholarship was granted, it is noteworthy that for the first time a comprehensive appraisal of the rural energy demand involving cooking, cooling, drying and lighting was conducted. The previous studies either focus on lighting or cooking for the rural areas and no attempt has been made in the past to comprehensively analyse various energy demands and provide a sustainable solutions to such demands for a typical village in Nigeria and Sub-Saharan Africa at large. More importantly, attempt has not been made in the past to use CHP system for rural applications such that drying and cold storage of agricultural products are synchronised with the generation of electricity.

Therefore, for a typical village in Nigeria, this study for the first time presents the report of a

- Systematic study on: the farmers' energy demands; renewable bio-wastes resources available locally and the potential of using such wastes to generate biogas for cooking and fuelling of an internal combustion engine for electricity and heat generation.
- A holistic solution – for agricultural products processing and preservation using renewable bio-waste and this approach will increase the farmers' standard of living, generation of income and improve food security.

Hence, based on the study objectives, Chapter 3 detailed the current energy usage and demand of the farmers in the study area. More than one energy sources are being used for lighting and cooking by the villagers. Kerosene lamps, touch light and mobile phone are predominantly being used for lighting with 100% of the farmers reported using kerosene lamps while 78%, 72%, 66% and 4% reportedly use touch light (disposable dry cell battery), rechargeable lamp, mobile phone and generator respectively. About 96% of the farmers uses fuelwood for cooking while kerosene is also being used especially during raining seasons when it is bushy and challenging getting fuelwoods. Fuelwood are also reportedly getting wet during these periods and it takes longer time to get fuelwood ignited. Hence, more kerosene stoves or charcoal are used during these seasons. At the moment, drying is done with open sun- drying using natural rocks, concrete slabs or polymer sheets. This drying method do affect the quality of their farm products especially during the raining seasons.

Household farm size was estimated to be 2.7 ha. Cassava, tomato, maize and cashew were identified as the major crops being grown in the community. The proportion of the farmers' land currently occupied by these crops had been used to evaluate farming energy requirements. Through the field study on the selected non-grid connected community and a grid connected village, this study was able to estimate the demand of energy as 35,475.00 kJ/day, 907.17 kJ/day; 30,879.40 kJ/day and 2250 kWh respectively for cooking, cooling, drying and lighting.

Chapter 4 detailed prevalence of post-harvest loss of agricultural produce within the study area which was x-rayed through analysis of the post-harvest handling of tomato. It is observed that about 31.3% estimated at 1.01 to 1.16 tons of tomato is being lost per hectare during the postharvest handling operations. Although, this is below between 50% and 90% PHL reported for tomato which could be attributed to the adoption of new and improved seedlings by the farmers that is able to withstanding some of the challenges of the postharvest handling operations. The International Institute of Tropical Agriculture, Ibadan has been working closely with farmers on improved seedlings and innovative PH handling systems and this might have contributed to a sharp reduction in the PH waste of tomato. Notwithstanding the differences, PHL of one-third of agricultural products is quite enormous and possess great challenge to food security while leaving the farmers on continuous abject poverty. Hence, need for a reliable and affordable solution to the PH waste.

As highlighted in the Chapter 5, about 48.9 tons/day of agricultural residue comprises of cattle market waste, cassava waste, cashew apple residue, maize stover and tomato residue can be technically collected from the study area. This can be anaerobically digested at 35^0C in five $1200m^3$ digesters to produce a 4,666.32kg/day biogas containing 55% methane. The produced biogas is 1.5% more than what is required by the 420 rural households to meet their energy demand for lighting, cooking, drying and cold storage of agricultural products. The anaerobic digestion process was carried out using an improved model of earlier works which was adapted to be able to predict the effects of pertinent parameters such as the organic loading rates, hydraulic retention time and pH on anaerobic digestion process.

A biogas fuelled internal combustion engine poly-generation system that can satisfy the village energy demand was investigated. The recovery of heat for drying, heating of anaerobic digester and cold storage of agricultural products increases the system efficiency from 26.73% for electricity only to about 74.5% for the CCHP mode. The results of the economic analysis indicate that, from the investors' perspective, the Rural Electrification Agency's electricity price of USD $0.420\cdot kWh^{-1}$ looks good with the discounted payback periods within less than 4 years thresholds for the analysed scenarios provided that the capital is not borrowed from the Nigerian commercial banks.

However, while this electricity pricing approach appears good from the investors' perspective, it is rather unfair to the rural dwellers. It puts extra burden of higher electricity tariff payment on already impoverished rural dweller majority of whom are currently living below poverty line of $USD2\cdot day^{-1}$. Three other tariffs were therefore analysed: USD0.013/kWh currently paid by the grid connected rural households; USD0.089/kWh being the current tariff for the poor urban households; and USD0.05/kWh which is considered as being moderate. At these lower prices of electricity, income from processing of agricultural products plays significant roles in the economy of the system. However, this role is influenced by the type and nature of the agricultural products processed. The results of the economic analysis indicate that USD0.013/kWh is not economical as all economical indices are negative. CHP for either drying or cold storage of agricultural product is only feasible at USD0.089/kWh and equally sensitive to the price volatility of agricultural products. With the payback period varying between 2.5-4.7 years, tri-generation system looks better with shorter payback period and with some resistance to changing in prices of agricultural products perhaps due to multiple income streams. The poly-generation system can both be operated with farmers paying for biogas and swapping of biomass for cooking biogas. However, the plant is better operated with the farmers paying for biogas while biomass is purchased. At these two operational systems the discounted payback periods are 4.89 years and 6.58 years respectively.

Currently, about 28.5% representing about 1.04 ton/ha of tomato is being lost between farm and the market within the studied area. Market glutting is responsible for about 13.3% of the lost. The use of village level CCHP system can address this challenge. This is because market rush is the only available option for the farmers at the moment as there is no storage facility. The rush does result in oversupply, crashing of price and abandonment in some cases. Hence, availability of cold storage will be able to reduce this challenge.

The study offers an understanding into a possible application of CCHP in agrarian communities of Nigeria and the SSA region in general. At the moment, most electrification systems are mono generated with electricity as the only product and source of income. Profitability of mono-generated system particularly becomes challenging in rural areas due to higher operation and maintenance cost compared to urban systems. This probably explains why, despite proposed increased tariffs, investment in rural electrification has not generated expected interest from both the investors and consumers. Rural communities seem to be reluctant in committing binding 20 years to high electricity tariff of USD0.42/kWh that does not have direct bearing to their economic activities. On the part of the investors, it appears that the risks and high operation and maintenance costs associated with rural electrification projects overshadow the effect of increased tariff. Hence, findings of this study suggest that it is possible to maintain a low-tariff electricity system with sensible IRR without unnecessarily putting the burden of extra payment on already impoverished smallholders' farmers. Drying and cold storage of agricultural products which make such generation to have direct impact on the economic upliftment of the farmers make the system attractive to rural communities.

However, the study indicates that system will benefit from the processing of more cash or industrial crops than staple food crops.

7.3 Recommendations for future work

This thesis has contributed to some fundamental findings in applications of CHP in agrarian communities of Nigeria and Sub-Saharan Africa region by extension. The prospect of biomass CHP in this regard has been highlighted particularly how this matured technology can be simultaneously used to reduce energy poverty as well lowering problems of post-harvest waste. The adoption of this technology can guarantee energy security since locally available resources are utilised. It is also unique in closing the nutrients loop through provision of organic fertiliser thereby making the agricultural activities more sustainable. However, generalisation of this study is limited and in paving way forward, further works as expatiated below should be studied in more detail:

- The CCHP evaluated in this work is based on simulation. A prototype of this configuration would be required for real analysis and the results from such experimental study could be used for further validation and generalisation of this study.
- A demonstration community-based CCHP system would be required for a further study on the effective thermal management of the system. For instance, the demand for cold storage or drying of agricultural products is influenced by seasons and type of agricultural practices. Hence, depending on these factors, there must be a trade-off between drying and cold storage.
- From the above demonstration plant, the social impact of this type of energy delivery system need to be studied. Such study would reveal where improvements and adjustments would be required.

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Appendices

Appendix 1: Sample of the questionnaire.

This questionnaire is meant to identify rural energy usage and post-harvest losses at the farm level. The information provided will be strictly treated as confidential and will be used for research purposes only. Your support will be greatly appreciated.

You are requested to: provide the real account to the questionnaire provided; seek clarification if need arises and tick where appropriate.

SECTION A: Demography of respondents

1	**What is your gender?**
Male	
Female	

2	**How old are you?**	
Less than 15		
16-35		
36-55		
Above 55		

3	**What is your marital**
Married	
Single	
Divorced	
Separated	
Widow	

4	**What is your education status?**	
None		
Primary		
Secondary		
Tertiary		

5	**What is the size of your family?**	
3		
4		
5		
6		
Greater than 6		

SECTION B: Energy usage

6. Type of house

A	Multiple family	
B	Single family	
C	Others	

If your answer is A, how many families are living in the house……………………………………………..?

7. Number of rooms/house

1	
2	
3	
4	
5	
Above 6	

8. What is the source of your lighting power?

Source	**Number**	**Rating**
Generator		
Electricity		
Kerosene lantern		
Rechargeable lamps		
Mobile phone		
Touch light (Battery)		
Others		

9. What is the source of your cooking power?

Source	**Number**	**Rating**
Charcoal		
Fuelwood		
Kerosene		
Cooking gas		
Hot plate		
Others		

10. What quantity of the above do you use/month?

Source	**Unit**	**Quantity**
Charcoal	Kg	
Fuelwood	Kg	
Kerosene	L	
Cooking gas	Kg	
Hot plate	kW	
Others		

11. Which of the following do you have and for how long are they used daily?

Load	Number	Power rating	Usage time(s)	Duration
Electricity				
lightning				
Radio				
Television				
Refrigeration				
Mobile phone				
Rechargeable lamp				
Fan				
Iron				
Hot plate				
Others				

SECTION C: Farming activities and Post-harvest loss

12	**What is your farm size**	
Less than 1		
2-3		
4-5		
Above 6		

13	**Which of the following crops do you plant?**
Cassava	
Yam	
Maize	
Sorghum	
Vegetables	
Tomato	
Melon	
Cocoa	
Cashew	

14	**Indicate size (acre) of your land under production of the following crops**
Cassava	
Yam	
Maize	
Sorghum	
Tomato	
Melon	
Cocoa	
Cashew	

15	**Indicate the number of times you grow these crops in a year.**			
Crops	**Once**	**Twice**	**Thrice**	**Others**
Cassava				
Yam				
Maize				
Sorghum				
Tomato				
Melon				
Cocoa				
Cashew				

16	**Indicate the number of times you harvest these crops in a year.**			
Crops	**Once**	**Twice**	**Thrice**	**Others**
Cassava				
Yam				
Maize				
Sorghum				
Tomato				
Melon				
Cocoa				
Cashew				

17. Which of the following do you consider the most wasteful during post-harvesting? Kindly rank in order of wastefulness with 1 being the most-wasted crop

Cassava	
Yam	
Maize	
Sorghum	
Tomato	
Melon	
Cocoa	
Cashew	

18. Kindly describe the extent of wastefulness of these crops

CROP	Severe	Enormous	Mild	Not wasted
Cassava				
Yam				
Maize				
Sorghum				
Tomato				
Melon				
Cocoa				
Cashew				

19. To what extent do you agree with the following statement?

	Strongly agree	Tend to agree	Neither agree nor disagree	Tend to Disagree	Strongly disagree
Crop wastage is creating huge economic loss for the farmer.					
Crop wastage is not creating huge economic loss for the farmer.					

20. To what extent do you agree with the following statement?

	Strongly agree	Tend to agree	Neither agree nor disagree	Tend to Disagree	Strongly disagree
Provision of basic food processing equipments will reduce post-harvest waste					
Provision of electricity will reduce post-harvest loss					

Provision of storage facilities will reduce post-harvest loss					
Government should provide drying drying equipments					

Appendix 2: Prototype of a water scrubber

Appendix 3: Kinetic equations used in the model (Angelidaki et al (Irini Angelidaki et al., 1999))

Disintegration steps	**Kinetic equations**
Degradation of acidogenic glucose	$$\mu = \mu_{max}(T) * \left(\frac{1}{1 + \frac{K_s}{[(C_6H_{10}O_5)_S]}} \right) * \left(\frac{1}{1 + \frac{K_{s,NH3}}{[T - NH_3]}} \right) \left(\frac{1}{1 + \frac{[LCFA]}{K_{i,LCFA}}} \right) F(pH)$$

Lipolytic degradation	$$\mu = \mu_{max}(T) * \left(\frac{1}{1+\frac{K_s}{[GTO]}}\right) * \left(\frac{1}{1+\frac{K_{s,NH3}}{[T-NH_3]}}\right)\left(\frac{1}{1+\frac{[LCFA]}{K_{i,LCFA}}}\right)F(pH)$$
Long Chain Fatty acid degradation (LCFA)	$$\mu = \mu_{max}(T) * \left(\frac{1}{1+\frac{K_{s,LCFA}}{[LCFA]}+\frac{[LCFA]}{K_{i,LCFA}}}\right) * \left(\frac{1}{1+\frac{K_{s,NH3}}{[T-NH_3]}}\right)F(pH)$$
Acetogenic step	$$\mu = \mu_{max}(T) * \left(\frac{1}{1+\frac{K_s}{[A]}}\right)\left(\frac{1}{1+\frac{[HAc]}{K_{i,HAc}}}\right) * \left(\frac{1}{1+\frac{K_{s,NH3}}{[T-NH_3]}}\right)\left(\frac{1}{1+\frac{[LCFA]}{K_{i,LCFA}}}\right)F(pH)$$
Methanogenic acetoclastic degradation	$$\mu = \mu_{max}(T) * \left(\frac{1}{1+\frac{K_s}{[HAc]}}\right)\left(\frac{1}{1+\frac{[NH3]}{K_{i,NH3}}}\right) * \left(\frac{1}{1+\frac{K_{s,NH3}}{[T-NH_3]}}\right)\left(\frac{1}{1+\frac{[LCFA]}{K_{i,LCFA}}}\right)F(pH)$$
pH effect	$F(pH) = e^{\left(-3*\left(\frac{pH-pH_{UL}}{pH-pH_{LL}}\right)^2\right)}$ For pH < pH_{UL} $F(pH) = 1$ For pH > pH_{UL}

Where: "S is the substrate for insoluble carbohydrates or for the insoluble proteins; k is the reaction rate; μ_{max} (T) is the temperature-dependent maximum specific growth rate; Ki is the half-saturation constant; Ks, NH3 is the half saturation constant for total ammonia; [T-NH3] is the total ammonia concentration; Ki denotes inhibition constants. F (pH) is the pH growth-modulating function.”

Appendix 4: Kinetic constants for thermophilic process (Angelidaki et al (I. Angelidaki et al., 1999; D. J. Batstone et al., 2002))

Group	**K_{max} (d^{-1})**	**E_A (J/kmol)**	**K_s(g/L)**	**m****	**$Ks,_{NH3}$ (g/L)**	**Ki (g/L)**	**m****	**Ki, $_{LCFA}$ (g/L)**	**$Ki,_{H2}$ (g/L)**	**m****	**pH_{LL}**	**pH_{UL}**
LCFA-degraders	10	$2.147*10^{7}$	0.02	0	0.05	-		5	$5.03*10^{-6}$	$2.5*10^{-7}$	4*	5.5*
Amino-acid degraders	70	$1.414*10^{7}$	0.3	0	-	-		-	-		4*	5.5*
Propionate degraders	20	$1.811*10^{7}$	0.259	0.01	0.05	0.96		5	$1*10^{-5}$	$3.2*10^{-7}$	4*	5.5*
Butyrate degraders	30	$1.704*10^{7}$	0.176	0.01	0.05	0.72		5	$3*10^{-5}$	$1*10^{-6}$	4*	5.5*
Valerate degraders	30	$1.704*10^{7}$	0.175	0.01	0.05	0.4		5	$3*10^{-5}$	$1*10^{-6}$	4*	5.5*

Methanogen	16	$2.914*10^7$	0.120	$7.5*10^{-3}$	0.05	0.26	$4.6*10^{-4}$	5	-		6	7
Hydrogen utilizing step	35	Equilibrium	0	$2.15*10^{-6}$	-	-		-	-		5	6

Appendix 5: The kinetic constants for the mesophilic process.

Group	**K_{max}[4] (d^{-1})**	**E_A[1] (J/kmol)**	**Ks[4] (g/l)**	**m****	**[2]K_{s,NH_3} (g/l)**	**Ki[3] (g/l)**	**m****	**[3]$K_{i,LCFA}$ (g/l)**	**[3]K_{i,H_2} (g/l)**	**m****	**pH[3] LL**	**pH[3] UL**
LCFA-degraders	6	$2.147*10^7$	0.4	0	0.05	-		2.56	$5*10^{-6}$	118.50	4*	5.5*
Amino-acid degraders	50	$1.414*10^7$	0.3	0	-	-		-	-		4*	5.5*

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[1] I. W. A. T. G. M. M. A. D, P. (2002) *Anaerobic Digestion Model No. 1 (ADM1)*. IWA.

[2] Hashimoto, A.G., Varel, V.H. and Chen, Y.R. (1981) 'Ultimate methane yield from beef cattle manure: Effect of temperature, ration constituents, antibiotics and manure age', *Agricultural Wastes*, 3(4), pp. 241-256, Angelidaki, I., Ellegaard, L. and Ahring, B.K. (1999) 'A comprehensive model of anaerobic bioconversion of complex substrates to biogas', *Biotechnology and Bioengineering*, 63(3), pp. 363-372.

[3] Astals, S., Batstone, D.J., Mata-Alvarez, J. and Jensen, P.D. (2014) 'Identification of synergistic impacts during anaerobic co-digestion of organic wastes', *Bioresource Technology*, 169, pp. 421-427.

Propionate degraders	15[4]	$1.811*10^{7}$	0.1	0.005	0.05	0.96		2.56	$3.5*10^{-6}$	$-1.25*10^{-6}$	4*	5.5*
Butyrate degraders	20	$1.704*10^{7}$	0.2	0.005	0.05	0.72		2.56	$1*10^{-5}$	$1*10^{-6}$	4*	5.5*
Valerate degraders	20	$1.704*10^{7}$	0.2	0.005	0.05	0.4		2.56	$1*10^{-5}$	$1*10^{-6}$	4*	5.5*
Methanogen	11[5]	$2.914*10^{7}$	0.15	0.0075	0.05	0.26	$4.95*10^{-4}$	-	-		6	7
Hydrogen utilizing step	35	Equilibrium	$7x10^{-6}$	$2.15 * 10^{-6}$	-	-		-	-		5	6

Appendix 6: Model simulation results at 35^{0}C

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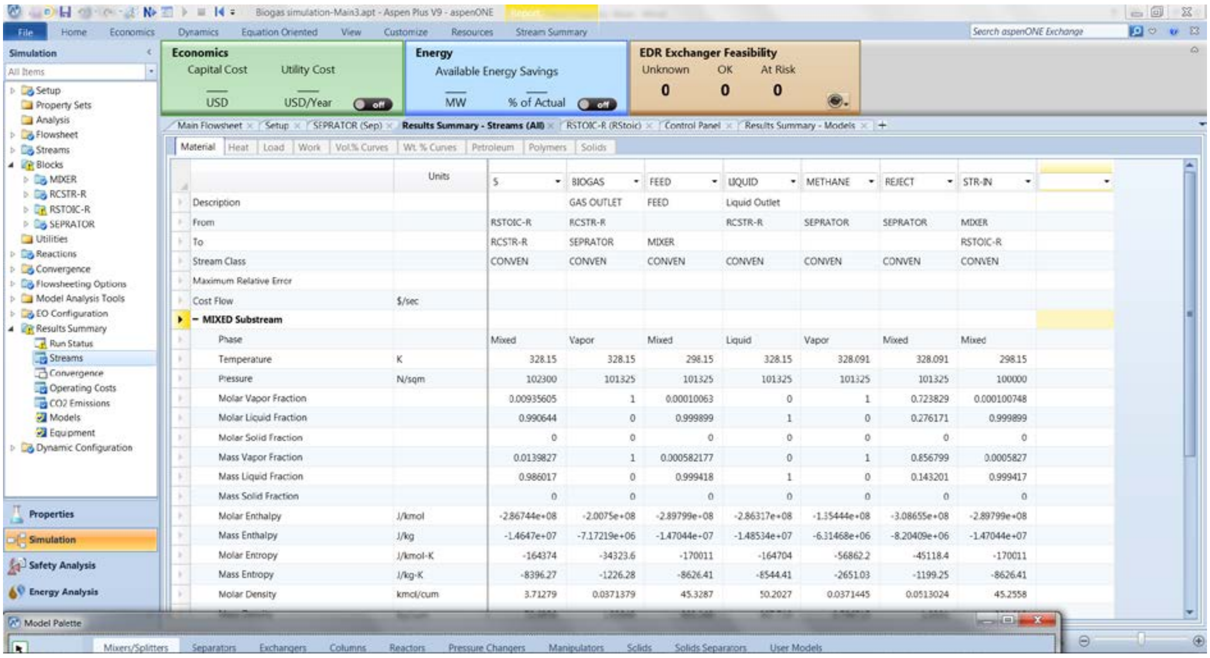
[4] Vega De Lille, M.I.-c. (2015) *Modeling, Simulation and Control of Biotechnological Processes in Decentralized Anaerobic Treatment of Domestic Wastewater Modellierung, Simulation und Regelung von biotechnologischen Prozessen zur dezentralen anaeroben Aufbereitung von häuslichem Abwasser* [Online]. Available at: https://opus4.kobv.de/opus4-fau/frontdoor/index/index/docId/6391 http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:29-opus4-63917.

State points	From	To	Pressure (bar)	Temperature (C)	Vapour Fraction	Mass flowrate (kg/hr)	NH3 Mass Fraction (%)
1A	Absorber	Pump	4.936	45.20	0	90.718	0.451
1B	Absorber	Pump	4.936	44.00	0	90.918	0.451
2	Pump	Rectifier	22.38	45.37	0	90.918	0.451
3	Rectifier	Pre-absorber A	4.938	115.29	0	55.057	0.093
4	Pre-absorber B	Generator	22.38	99.28	0	90.718	0.451
5	Generator	Condenser	22.38	63.70	0	90.718	0.451
6	Generator	Exch	22.38	115.00	0	55.057	0.093
7	PreabA	Preab-B	22.38	102.07	1	35.66	0.977
8	Condenser	Refrigerant Heatx	22.38	48.5	0	35.66	0.977
9	Refrigerant Heatx	Valve1	4.936	4.73	0.069	35.66	0.977
10	Valve1	Evaporator	4.936	7.051	0.755	35.66	0.977
11	Evaporator	Refrigerant Heatx	4.938	9.52	0.851	35.66	0.977

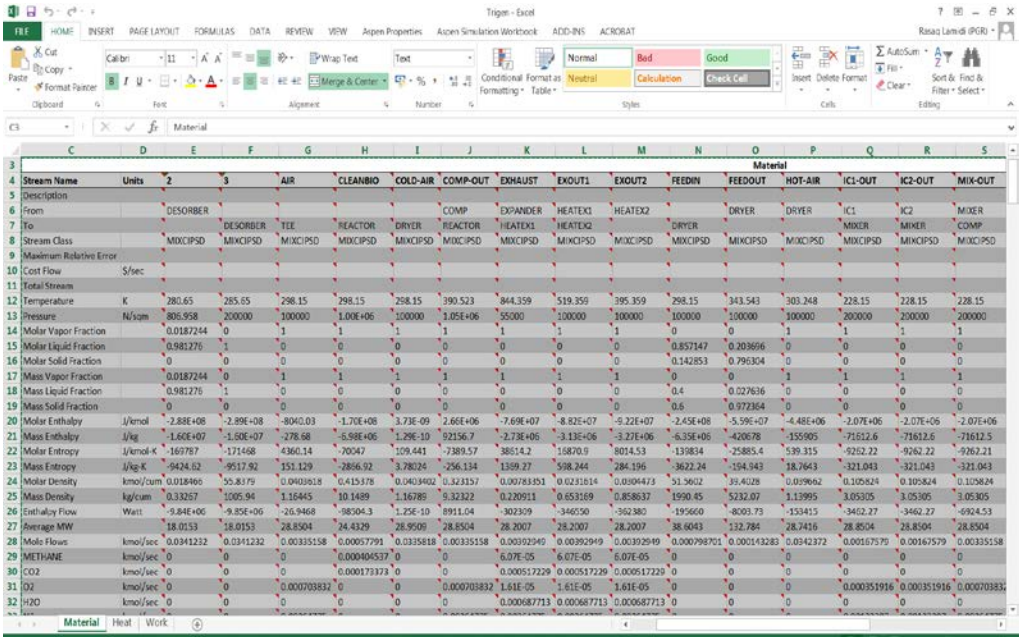
12	Refrigerant Heatx	Preab-A	4.938	76.00	1	25.07	0.949
13	Exch	Valve2	22.38	23.05	0	25.66	0.977
14	Valve2	Preab-A	4.938	76.00	0.262	90.718	0.451
15	Pre-absorber A	Mixer	4.938	76.00	0	67.65	0.274

Appendix 7: Biogas simulation result stream summary



	Units	S	BIOGAS	FEED	LIQUID	METHANE	REJECT	STR-IN
Description			GAS OUTLET	FEED	Liquid Outlet			
From		RSTOIC-R	RCSTR-R		RCSTR-R	SEPRATOR	SEPRATOR	MIXER
To		RCSTR-R	SEPRATOR	MIXER				RSTOIC-R
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error								
Cost Flow	$/sec							
− MIXED Substream								
Phase		Mixed	Vapor	Mixed	Liquid	Vapor	Mixed	Mixed
Temperature	K	328.15	328.15	298.15	328.15	328.091	328.091	298.15
Pressure	N/sqm	102300	101325	101325	101325	101325	101325	100000
Molar Vapor Fraction		0.00935605	1	0.00010063	0	1	0.723829	0.000100748
Molar Liquid Fraction		0.990644	0	0.999899	1	0	0.276171	0.999899
Molar Solid Fraction		0	0	0	0	0	0	0
Mass Vapor Fraction		0.0139827	1	0.000582177	0	1	0.856799	0.0005827
Mass Liquid Fraction		0.986017	0	0.999418	1	0	0.143201	0.999417
Mass Solid Fraction		0	0	0	0	0	0	0
Molar Enthalpy	J/kmol	-2.86744e+08	-2.0075e+08	-2.89799e+08	-2.86317e+08	-1.35444e+08	-3.08655e+08	-2.89799e+08
Mass Enthalpy	J/kg	-1.4647e+07	-7.17219e+06	-1.47044e+07	-1.48534e+07	-6.31468e+06	-8.20409e+06	-1.47044e+07
Molar Entropy	J/kmol-K	-164374	-34323.6	-170011	-164704	-56862.2	-45118.4	-170011
Mass Entropy	J/kg-K	-8396.27	-1226.28	-8626.41	-8544.41	-2651.03	-1199.25	-8626.41
Molar Density	kmol/cum	3.71279	0.0371379	45.3287	50.2027	0.0371445	0.0513024	45.2558

Appendix 8: Trigeneration streams results in Aspen APW.



	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
3													Material				
4	**Stream Name**	**Units**	**2**	**3**	**AIR**	**CLEANBIO**	**COLD-AIR**	**COMP-OUT**	**EXHAUST**	**EXOUT1**	**EXOUT2**	**FEEDIN**	**FEEDOUT**	**HOT-AIR**	**IC1-OUT**	**IC2-OUT**	**MIX-OUT**
5	Description																
6	From		DESORBER					COMP	EXPANDER	HEATEX1	HEATEX2		DRYER	DRYER	IC1	IC2	MIXER
7	To			DESORBER	TEE	REACTOR	DRYER	REACTOR	HEATEX1	HEATEX2		DRYER			MIXER	MIXER	COMP
8	Stream Class		MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD	MIXCIPSD
9	Maximum Relative Error																
10	Cost Flow	$/sec															
11	Total Stream																
12	Temperature	K	280.65	285.65	298.15	298.15	298.15	390.523	844.359	519.359	395.359	298.15	343.543	303.248	228.15	228.15	228.15
13	Pressure	N/sqm	806.958	200000	100000	1.00E+06	100000	1.05E+06	55000	100000	100000	100000	100000	100000	200000	200000	200000
14	Molar Vapor Fraction		0.0187244	0	1	1	1	1	1	1	1	0	0	1	1	1	1
15	Molar Liquid Fraction		0.981276	1	0	0	0	0	0	0	0	0.857147	0.203696	0	0	0	0
16	Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0.142853	0.796304	0	0	0	0
17	Mass Vapor Fraction		0.0187244	0	1	1	1	1	1	1	1	0	0	1	1	1	1
18	Mass Liquid Fraction		0.981276	1	0	0	0	0	0	0	0	0.4	0.027636	0	0	0	0
19	Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0.6	0.972364	0	0	0	0
20	Molar Enthalpy	J/kmol	-2.88E+08	-2.89E+08	-8040.03	-1.70E+08	3.73E-09	2.66E+06	-7.69E+07	-8.82E+07	-9.22E+07	-2.45E+08	-5.59E+07	-4.48E+06	-2.07E+06	-2.07E+06	-2.07E+06
21	Mass Enthalpy	J/kg	-1.60E+07	-1.60E+07	-278.68	-6.98E+06	1.29E-10	92156.7	-2.73E+06	-3.13E+06	-3.27E+06	-6.35E+06	-420678	-155905	-71612.6	-71612.6	-71612.5
22	Molar Entropy	J/kmol-K	-169787	-171468	4360.14	-70047	109.441	-7389.57	38614.2	16870.9	8014.53	-139834	-25885.4	539.315	-9262.22	-9262.22	-9262.21
23	Mass Entropy	J/kg-K	-9424.62	-9517.92	151.129	-2866.92	3.78024	-256.134	1369.27	598.244	284.196	-3622.24	-194.943	18.7643	-321.043	-321.043	-321.043
24	Molar Density	kmol/cum	0.018466	55.8379	0.0403618	0.415378	0.0403402	0.323157	0.00783351	0.0231614	0.0304473	51.5602	39.4028	0.039662	0.105824	0.105824	0.105824
25	Mass Density	kg/cum	0.33267	1005.94	1.16445	10.1489	1.16789	9.32322	0.220911	0.653169	0.858637	1990.45	5232.07	1.13995	3.05305	3.05305	3.05305
26	Enthalpy Flow	Watt	-9.84E+06	-9.85E+06	-26.9468	-98504.3	1.25E-10	8911.04	-302309	-346550	-362380	-195660	-8003.73	-153415	-3462.27	-3462.27	-6924.53
27	Average MW		18.0153	18.0153	28.8504	24.4329	28.9509	28.8504	28.2007	28.2007	28.2007	38.6043	132.784	28.7416	28.8504	28.8504	28.8504
28	Mole Flows	kmol/sec	0.0341232	0.0341232	0.00335158	0.00057791	0.0335818	0.00335158	0.00392949	0.00392949	0.00392949	0.000798701	0.000143283	0.0342372	0.00167579	0.00167579	0.00335158
29	METHANE	kmol/sec	0	0	0	0.000404537	0	0	6.07E-05	6.07E-05	6.07E-05	0	0	0	0	0	0
30	CO2	kmol/sec	0	0	0	0.000173373	0	0	0.000517229	0.000517229	0.000517229	0	0	0	0	0	0
31	O2	kmol/sec	0	0	0.000703832	0	0	0.000703832	1.61E-05	1.61E-05	1.61E-05	0	0	0	0.000351916	0.000351916	0.00070383
32	H2O	kmol/sec	0	0	0	0	0	0	0.000687713	0.000687713	0.000687713	0	0	0	0	0	0