Potential and Economic Impact of Renewable Energy in Improving African Rural Food Processing

by

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Thesis presented in partial fulfilment
of the requirements for the Degree

of

MASTER OF ENGINEERING
(CHEMICAL ENGINEERING)

in the Faculty of Engineering
at Stellenbosch University

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March 2016

Declaration

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Date: March 2016

SUMMARY

Traditional food processing technologies in rural settings of Sub Saharan Africa are characterised by small production scales, labour intensive processes and uneconomical operations, which contribute to high food losses postharvest. Mechanisation addresses some of these limitations although a lack of access to modern energy stands as additional drawback. Hence in order for advancing mechanisation to be feasible, an alternative approach to integrating energy supply into food processing systems is required. Little is known on the cost implications of such mechanisation and alternative energy integration on the profitability of the food processes.

The general objective of this study was to investigate the economic impacts of mechanisation and/or bioenergy integration in crude palm oil (CPO), cassava flour (CF) and maize flour (MF) processes. This objective was achieved by developing process models for traditional, semi-mechanised and mechanised processes, with increasing extent or level of mechanisation, in which in-house energy integration was applied. The process/economic models were developed using Microsoft Excel. For each of the referred processes, Base-cases (B/C) entailing conventional energy-mix and corresponding improved-cases (I/C) with potential energy from process residues (in-house energy) were considered. Models of advanced in-house energy schemes were developed in Aspen Plus®. Economics were based on 2014 economic conditions of Ghana. Two funding schemes were assessed: 1. Private investor financing [60% of investment financed by loan (at 24% nominal interest rate) and remaining 40% investment from equity (at 40% nominal interest rate), having weighted nominal (before inflation) discount rate of 30%]. 2. Combinations of grant (at 0% nominal discount rate) and equity (at 40% nominal discount rate) financing (i.e. part of the financing covered by grant and the remaining investment financed by equity from an investor).

Feasible advanced energy schemes considered in the I/C scenarios were: electricity/thermal energies from solid biomass residues for the CPO mechanised process, electricity/dryer fuel from anaerobic digestion of cassava peels/cattle dung for the CF semi- and mechanised process and, cob-fired dryer for MF semi- and mechanised drying operations.

In the CPO process, there was a decrease in energy demands for the mechanised process at the B/C and I/C levels when compared to the traditional (79.2 and 83.8%) and semi-mechanised (48 and 51%) respectively. Thus an increase in the level of mechanisation was

not necessarily associated with an increase in energy savings. In addition, under the private investor financing (nominal discount rate of 30%), only the mechanised process was economically viable with an Internal Rate of Return (IRR) of 47.2% under the B/C scenarios, while the semi- and mechanised processes were the economically viable options for the I/C scenarios with IRRs of 143% and 40.6% respectively. The poor performances of the traditional- B/C and -I/C and semi-mechanised B/C were due to combinations of high capital investment ($0.019 – 0.053/kg) and high production cost ($0.431 – 1.187/kg), as they remained unviable under 100% grant funding. Thus mechanisation is beneficial to the economics at the highest mechanised process level, while in-house energy integration from residues is most promising at the semi- and mechanised process levels.

In the CF Process, the energy demand for the traditional process was higher by 37.6, 44.5 and 52.6% (for B/C) and 46.0, 52.0 and 59.0% (for I/C) than the semi-mechanised, mechanised-grating and mechanised-chipping processes respectively. Thus, mechanisation has an energy saving impact on the process. Under the private investor funding (discount rate of 30%), the mechanised chipping process was the only economically viable option (IRR of 36.3%), while the traditional B/C, traditional I/C and mechanised-chipping B/C were promising with IRRs of 16.3, 24 and 24.8% respectively. Under grant-equity funding, semi-mechanised and mechanised-grating processes remained unviable, thus not being able to achieve sufficient cash flows to pay off debt co-financing of new installations. Under the grant-equity financing, the traditional B/C and I/C, and mechanised-chipping I/C processes achieved Net Present Values (NPV) of $22, $60 and $67180 at grant funding of 60%, 40% and 1% respectively (with the remaining funding contributions provided by equity), suggesting their potential viability under grant subsidy. Thus, economic impact of mechanisation and that of in-house energy generation from the residues were inconsistent.

The energy demand of the mechanised MF process was higher by 87.3 and 48.0% (B/C) and 89.1 and 51.2% (I/C) than the traditional and semi-mechanised scenarios, respectively. Conclusively, an increase in mechanisation also increased the process energy demands. All B/C scenarios attained negative NPVs and were thus economically unviable. The I/C scenario for the traditional process remained unviable with NPV of -$1854, while semi- and mechanised processes attained IRRs of 18.8 and 132.8% respectively; hence, only mechanised I/C was viable considering the 30% minimum expected IRR. At semi-mechanised I/C, feedstock obtained from farm gates rather than licensed buying companies (LBCs) resulted in production cost savings of 46.2%, while integration of cobs as dryer fuel

increased production cost by 25.5%. Sourcing feedstock from farm gates rather than LBCs and using cobs residues as dryer fuel (replacing diesel) in the mechanised I/C process, resulted in production cost savings of 73.2 and 1.7% respectively. The traditional, semi- and mechanised B/C processes remained unviable under 100% grant funding, while semi-mechanised I/C process attained NPV of $1422 at 40% grant and 60% equity financing. Therefore, mechanisation did not improve economic performance; rather feedstock supply chain was the determining factor for profitability of MF processing. Cobs-fuelling dryer was technically viable but most beneficial (economically) to the mechanised process.

OPSOMMING

Tradisionele voedsel verwerking tegnologieë in landelike omgewings van Sub-Sahara Afrika word gekenmerk deur 'n klein produksie skale, asook arbeidsintensiewe en onekonomies prosesse, wat bydra tot hoë na-oes voedselverliese. Alhoewel meganisasie hierdie beperkings adresseer, is 'n gebrek aan toegang tot moderne energie 'n bykomende nadeel. Gevolglik, om die bevordering van meganisasie haalbaar te maak, is 'n alternatiewe benadering tot die integrasie van energievoorsiening in voedsel verwerking stelsels nodig. Min is bekend oor die koste-implikasies van sodanige meganisasie en die effek van alternatiewe energie integrasie op die winsgewendheid van die voedsel prosesse.

Die algemene doelwit van hierdie studie was om die ekonomiese impak van meganisasie en/of bio-energie integrasie in ru palmolie (RPO), 'cassava'-meel (CM) en mieliemeel (MM) prosesse te ondersoek. Hierdie doelwit is bereik deur die ontwikkeling van proses modelle vir tradisionele, semi-gemeganiseerde en gemeganiseerde prosesse, met toenemende mate of vlak van meganisasie, met die toepassing van in-huis energie-integrasie. Die proses/ekonomiese modelle is ontwikkel met behulp van Microsoft Excel. Vir elk van die prosesse na verwys, is basis-gevalle (B/G) wat konvensionele energie-mengsel behels en ooreenstemmende verbeterde-gevalle (V/G) met potensiële energie van die proses reste (in-huis energie) oorweeg. Modelle met gevorderde in-huis-energie skemas was ontwikkel in Aspen Plus®. Die ekonomiese studie is gebaseer op 2014 ekonomiese toestande van Ghana. Twee befondsing skemas was geëvalueer: 1. Privaat belegger finansiering [60% van die belegging gefinansier deur lening (teen 24% nominale rentekoers) en oorblywende 40% van die belegging van ekwiteit (teen 40% nominale rentekoers), met geweegde nominale (voor inflasie) verdiskonteringskoers van 30%]. 2. Kombinasies van subsidie (teen 0% nominale verdiskonteringskoers) en ekwiteit (teen 40% nominale verdiskonteringskoers) finansiering (d.w.s. 'n deel van die finansiering word deur die subsidie gedek word terwyl die oorblywende belegging deur ekwiteit van 'n belegger gefinansier word).

Gevorderde energie skemas oorweeg in die V/G scenario's was: elektrisiteit/termiese energie van vaste biomassa reste vir die RPO gemeganiseerde proses, elektrisiteit/droër brandstof van anaërobiese vertering van 'cassava' skille/beesmis vir die CM semi- en gemeganiseerde proses en mieliekop-aangedrewe droër vir MM semi- en gemeganiseerde droging prosesse.
In die RPO proses was daar 'n afname in energie vereistes vir die gemeganiseerde proses by die B/G en V/G vlakke in vergelyking met die tradisionele (79.2 en 83.8%) en semi-

gemeganiseerde (48 en 51%) onderskeidelik. Daar was dus nie noodwendig ’n direkte verband tussen 'n toename in die vlak van meganisasie en toename in energie gespaar nie. Daarbenewens, met private finansiering belegging (nominale verdiskonteringskoers van 30%), was slegs die gemeganiseerde proses ekonomies lewensvatbaar met 'n Interne Opbrengskoers (IOK) van 47.2% met die B/G scenario's, terwyl die semi- en gemeganiseerde prosesse was die ekonomies lewensvatbare opsies vir die V/G scenario’s met IOKe van 143% en 40.6% onderskeidelik. Die swak prestasies van die tradisionele B/G en V/G en semi-gemeganiseerde B/G was as gevolg van ’n kombinasie van hoë kapitale belegging ($0.019 – 0.053/kg) en hoë produksiekoste ($0.431 – 1.187/kg), aangesien hulle nie lewensvatbaar gebly het nie onder 100% subsidie befondsing. Meganisasie is dus voordelig vir die ekonomiese lewensvatbaarheid vir die hoogste gemeganiseerde proses vlak, terwyl in-huis energie-integrasie van reste mees belowend is vir die semi- en gemeganiseerde proses vlakke.

Vir die CM-proses was die energie aanvraag vir die tradisionele proses hoër met 37.6, 44.5 en 52.6% (vir B/G) en 46.0, 52.0 en 59.0% (vir V/G) as die semi-gemeganiseerde, gemeganiseerde-‘grating’ en gemeganiseerde-‘chipping’ prosesse onderskeidelik. Dus, meganisasie het 'n energiebesparende impak op die proses. Onder die private befondsing belegging (verdiskonteringskoers van 30%), was die gemeganiseerde ‘chipping’ proses die enigste ekonomies lewensvatbare opsie (IOK van 36.3%), terwyl die tradisionele B/G, tradisionele V/G en gemeganiseerde-‘chipping’ B/G belowend was met IOKe van 16.3, 24 en 24.8% onderskeidelik. Onder befondsing-ekwiteit finansiering, was die semi-gemeganiseerde en gemeganiseerde-‘grating’ prosesse steeds nie lewensvatbaar, dus nie in staat om voldoende kontantvloei te bereik om skuld mede-finansiering van nuwe installasies af te betaal.

Onder die befondsing-ekwiteit finansiering, het die tradisionele B/G en V/G en gemeganiseerde-‘chipping’ V/G prosesse Net Huidige Waardes (NHW) bereik van $22, $60 en $67180 op subsidie befondsing van 60%, 40% en 1% onderskeidelik (met die oorblywende befondsing bydraes deur ekwiteit), wat op hul lewensvatbaarheid onder befondsing subsidie dui. Dus, die ekonomiese impak van meganisasie en dié van in-huis energie-opwekking uit die reste was uiteenlopend.

Die energie aanvraag van die gemeganiseerde MM proses was hoër met 87.3 en 48.0% (B/G) en 89.1 en 51.2% (V/G) as die tradisionele en semi-gemeganiseerde scenario's, onderskeidelik. Onweerlegbaar, 'n toename in meganisasie verhoog die vereiste energie van die proses. Alle B/G scenario's het negatiewe NHWs bereik en was dus ekonomies onlewensvatbaar. Die V/G scenario vir die tradisionele proses het onlewensvatbaar gebly met NHW van -$1854, terwyl die semi- en gemeganiseerde prosesse IOK bereik het van 18.8 en 132.8% onderskeidelik; dus, net gemeganiseerde V/G was lewensvatbaar met oorweging van die 30% minimum verwagte IOK. Met semi-gemeganiseerde V/G, het die verkryging van roumateriaal vanaf plaashekke eerder as gelisensieerde koop maatskappye gelei tot n produksie koste besparing van 46.2%, terwyl die integrasie van mieliekoppe as droër brandstof produksie koste met 25.5% verhoog het. Verkryging van roumateriaal vanaf plaashekke eerder as gelisensieerde koop maatskappye en die gebruik van mieliekoppe reste as droër brandstof (diesel vervang) in die gemeganiseerde V/G proses, het gelei tot 'n produksie koste besparing van 73.2 en 1.7% onderskeidelik. Die tradisionele, semi- en gemeganiseerde B/G prosesse het onlewensvatbaar gebly onder 100% befondsing, terwyl die semi-gemeganiseerde V/G proses 'n NWH van $1422 bereik het op 40% befondsing en 60% ekwiteit finansiering. Meganisasie het dus nie die ekonomiese prestasie verbeter nie; eerder, die roumateriaal ketting was die bepalende faktor vir die winsgewendheid van die MM prosesse. Mieliekoppe as brandstof vir droër was tegnies lewensvatbaar maar mees voordelig (ekonomies) vir die gemeganiseerde proses.

ACKNOWLEDGEMENT

My last two years of research work would not have been a success without the support of the following personalities whom I would like to acknowledge:

First and foremost, I am grateful to God in all ways for seeing me through this study.

Dr. A.F.A. Chimphango, for her insightful ideas and guidance as she exposed me to the world of food and bioenergy research.

Prof. Johann Görgens, for his priceless support and supervision throughout the two years of my study.

Mr. Frank Nsaful and Mr. Roberto Agudelo, for their invaluable contributions and tips to a successful thesis.

Friends and colleagues in the Process Engineering Department of Stellenbosch University particularly the bio-refinery modelling research group for their shared ideas, academic contributions and motivations to press on.

Centre for Renewable and Sustainable Energy Studies (CRSES), for their vital financial assistance without which this study would have been but a dream.

RE4FOOD project sponsors for their valuable funding, and the project partners for their contributions to the success of the study.

Friends and families of the Stellenbosch Baptist church, especially Mama Heide and Papa Ulli, for their care and support throughout my stay in Stellenbosch.

To my family, particularly parents, for their fervent support and giving me a reason to run the race. I love you all for this!

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NOMENCLATURE

$/kW US dollar per kilowatt electricity

$/kWh US dollar per kilowatt-hour

$/m^3 US dollar per cubic meter

AD anaerobic digestion

B/C Base-Case

BCST Biomass Combustion Steam Turbine

CEPCI Chemical Engineering Plant Cost Index

CF Cassava Flour

CFU/ml Colony Forming Unit per millilitre

CHP Combined Heat and Power

CPO crude palm oil

$E_{elec\ power}$ net electric power output

efb empty fruit bunches

$E_{th\ biomass\ residue}$ thermal energy in biomass

$E_{th\ process}$ net thermal energy output

FCI Fixed Capital Investment

FFB Fresh Fruit Bunches

$H_{Biomass}$ thermal energy of biomass fuel input

HP high pressure

HQCF High Quality Cassava Flour

HRT hydraulic retention time

H_{useful} useful energy to process

I/C Improved Case

IRR Internal Rate of Return

l/kg-TS Litres per kilogram total solid

LBCs licenced buying companies

LHV Lower Heating Value

LP Low pressure

m^3/Mt cubic meter per metric ton

MF Maize Flour

mf mesocarp fibre

MJ/kg mega joule per kilogram

MW megawatt electric energy

MW_{th} megawatt thermal energy

$n_{overall}$ Overall CHP efficiency

NPV Net Present Value

O&M operation and maintenance costs

pks palm kernel shell

POME Palm Oil Mill Effluent

RETs Renewable Energy Technologies

SCI Specific Capital Investment

SOC Specific Operating Cost

SSA Sub Saharan Africa

TCI Total Capital Investment

TOC Total Operating Cost

TPC Total Production Cost

WC Working Capital

wt% weight percent

η_{th} thermal efficiency

1 INTRODUCTION

1.1 Background

The increase in industrial applications of agro-processed foods, such as crude palm oil in cooking oil and soup-mix applications, has increased their demand and consequently intensified interest in the expansion of their production capacities in sub-Saharan Africa (SSA) (FAO, 2012; Kleih *et al.*, 2013; Ofosu-Budu and Sarpong, 2013). This increasing demand has led to implementation of successful programmes in boosting the cultivation of the feedstock crops (FAO, 2012; Chauvin *et al.*, 2012). However, food processing remains a small-scale activity, executed with inefficient manually operated indigenous technologies. This results in high food losses (including post-harvest losses) of 120 - 170 kg/year and thus making the food industry unsustainable in the long run (Gustavsson *et al.*, 2011). Modern energy (electricity and fossil fuel) powered mechanised food processing technologies have been noted to address the set-backs of the indigenous technologies (Zu *et al.*, 2012; Dziedzoave *et al.*, 2003; Sanni, 1993). However, lack of inexpensive modern energy stands as a challenge to adopting the mechanised technologies as an alternative to the indigenous technologies.

Food processing integrates complex or simple technologies and practices in converting raw agricultural harvest into safe and lasting intermediates or final food products for consumers (Monteiro and Levy, 2010; Wang, 2009; Heldman and Hartel, 1997). The complexity of the conversion/isolation process determines the number of unit operations (stages) and technology requirements in the process (Truswell and Brand, 1985). Traditional technologies entail simple and indigenous equipment and techniques that are limited to specific products, such as a 'mortar and pestle' for pounding grain into flour, and are the prevalent technologies employed in African rural food processing (Aworh, 2008). Noted drawbacks of the dominating traditional technologies include low production capacity, labour intensive operations, uneconomical operations, low mass yields and energy conversion efficiency, and lack of product quality assurance (Ajao *et al.*, 2009; Lartey, 1975; Aworh, 2008). Thus, the processes are often limited to small-scale or subsistence-scale, and undertaken by the farmers or individual processers (Lado, 1992; Sefa-Dedeh, 1993).

Mechanisation, which is the replacement of human labour with machinery, of the traditional food processing approaches has been suggested as one of the main ways to improve the traditional rural food processing sector, to improve for the quality of products and the production capacity, to meet the growing local and industrial demands (Taiwo *et al*., 2002; Aworh, 2008; Sanni, 1993). Although mechanisation technologies for most traditional rural food processes are established, their adoption by rural processors remains minimal due to perceived high economic risk and the costly or unavailability of modern energy for powering the mechanized technologies (Kleih *et al*., 2013; FAO, 2012; Quaye *et al*., 2009). Therefore based on the level (extent) of mechanisation, rural food processes could be classified into traditional, semi-mechanised and mechanised processes (Aworh, 2008; Ouaouich, 2004; Dziedzoave *et al*., 2003; FAO, 2002). The former utilises traditional technologies, the semi-mechanised entails combination of traditional and mechanized technologies, and the latter entails the use of fully mechanised technologies (Aworh, 2008; Ouaouich, 2004; Dziedzoave *et al*., 2003; FAO, 2002).

The sustainability of mechanisation of the rural food processes requires consideration of alternative and affordable energy resources locally available, based on biomass (Belward *et al*., 2011; Ajoku, 2012). However, environmental detriments such as deforestation due to indiscriminate uses of biomass resources in activities such as cooking (Belward *et al*., 2011) is an additional drawback that demands strategic approach when considering biomass (bioenergy) in food processing. Typically, biomass wastes (residues) generated in the food processes are minimally exploited for energy purposes (Ajoku, 2012; Belward *et al*., 2011), and would be an appropriate source of process energy, with negligible environmental damage. The minimal exploitation of the residues is often as heating fuel combusted in inefficient cook-stoves (Belward *et al.*, 2011), while large portions of the residues are simply discarded as waste (Ajoku, 2012; Serpagli *et al*., 2012a). The process residues can be converted by established technologies such as anaerobic digesters for slurry residues and combustion technologies for lignocellulosic residues, to biogas and electricity respectively, for use in the food processes termed as in-house energy generation (Ajoku, 2012; Wang, 2009).

Conversions of some biomass residues from food processing to alternative energy forms have been studied. Belonio *et al*. (2012) investigated the technical feasibility of utilising maize cobs, rice husk and coconut husk residues as grain dryer fuel in maize and rice processing in Philippines. The study noted fuelling the grain dryers with the referred residues was technically feasible using a forced convection furnace. Adelekan (2012) evaluated the potential of converting cassava peels to biogas via anaerobic digestion. It was observed that the high portion of lignocellulose in the cassava peels makes it technically unviable as a biogas feedstock and needed to be combined with high-nitrogen, readily digestible co-feed to be technically viable, e.g. animal dung. Yeoh (2004) also assessed the technical and economic feasibility of generating electricity from biogas obtained from anaerobic digestion of Palm Oil mill Effluent (POME) under Malaysian context and found the process to be technically and economically feasible. Although extensive studies have established the potential of residue conversion to energy, little is known about the technical and economic feasibility of implementing the in-house energy generation in the developing SSA food processing context. Knowledge of the technical and economic (techno-economic) feasibility of in-house energy generation, in particularly the mechanised food processes, could be a practical way of addressing the aforementioned perceived economic risks by potential investors or food processors.

Process and economic modelling (techno-economic modelling) is a suite of detailed process and financial models developed using available technical or experimental data and can assist in techno-economic evaluations of various processes. Process and economic modelling has been used extensively in various energy processes or technology feasibility studies and proven to be adept for feasibility studies (Kempegowda *et al*., 2012; Serpagli *et al*., 2010a; Humbird *et al*., 2011). Thus, the implementation of process and economic modelling in the techno-economic feasibility assessment of mechanisation and in-house energy generation in the food processes will help avert misapplication of investments and efforts in implementing such projects.

Based on the above background, this study aimed at investigating the economic impacts of mechanisation and strategic in-house energy generation from the biomass residues in crude palm oil (CPO), cassava flour (CF) and maize flour (MF) processing, to contribute to the knowledge in bioenergy integration and feasible mechanisation alternatives in the SSA food processing context. This was achieved by developing process and economic models for three levels of mechanisation: traditional, semi-mechanised and mechanised. For each level of mechanisation, models for Base-Case (B/C) scenarios entailing current processing approaches with conventional energy-mix and corresponding Improved-Case (I/C) scenarios with potential in-house bioenergy integration was developed. The process and economic models were developed in Microsoft excel based on technical data from literature. Conservative assumptions based on the SSA conditions were made in the cases of nonexistence of literature. Advanced in-house energy generation process models were developed in Aspen Plus® to facilitate the sizing of equipment and energy outputs for consideration in the economic models for the I/C scenarios. Comparison of the outcomes for the B/C cases in each food process provided the basis for evaluating the economic impacts of mechanisation and comparing the outcomes of the B/C scenarios to their respective I/C scenarios provided the basis for assessing the economic benefits of in-house energy generation.

1.2 Motivation

High labour demand, conversion inefficiencies and low production capacities of traditional food processing technologies in African rural food processing have been identified as major constraints to improving rural food processing capacities. Addressing these through mechanisation and bio-energy supply could contribute to the reduction of post-harvest losses and improve rural livelihood. Although mechanisation is proposed as a solution to these challenges, the lack of modern energy (electricity and diesel) to run the mechanised technologies, in addition to perceived risk of non-profitability of mechanisation, limit its implementation. Hence, the improvement of rural food processing through mechanisation demands integration of alternative cheaper energy resources locally available as a realistic approach. Likewise, techno-economic assessment as a feasibility evaluation tool must be integrally incorporated to relieve the economic risk associated with mechanisation.

1.3 Objectives

The general objective of the study was to evaluate the economic impacts of mechanization and strategic integration of bioenergy in selected rural food processes: cassava flour, crude palm oil and maize flour.

In order to achieve the general objective, the following specific objectives were investigated:

1 To develop process models of traditional, semi-mechanised and mechanised crude palm oil (CPO), cassava flour (CF) and maize flour (MF) production processes based on technical data from literature or conservative assumptions from field observations. The outcome is intended to provide the impact of mechanisation on the process energy demands in addition to identifying potential avenues for renewable energy integration into the processes.

2 To develop process models for conversion of the process biomass residues comprising CPO solid (mesocarp-fibre, empty fruit bunch, and palm kernel shells) and palm oil mill effluent (POME), maize cobs, and cassava peels to in-house energies in the CPO, MF and CF processes respectively. This is to enable determine the feasibility and potential contributions of each residue to the energy requirements of the respective food processes.

3 To perform economic assessments of the modelled CPO, CF and MF processes and their respective in-house energy processes to estimate the economic impact of mechanisation and integration of in-house energy in the food processes.

1.4 Significance of the Study

The findings from this study will be instrumental to stakeholders in decision making concerning improving rural food processing and livelihood. In particular, the study contributes to the feasibility of mechanisation and alternative energy integration in rural food processing as it gives a total economic foundation of different scenarios of mechanisation and energy integrations in the referred food processes.

1.5 Thesis Layout

The layout of the thesis is summarised in Figure 1-1. Chapter 1 presents a general introduction and the objectives of the study. Chapter 2 presents a general literature study on the selected crude palm oil (CPO), cassava flour (CF) and maize flour (MF) processing approaches. Regional (African) issues on energy and its demand in food processing were also presented. Concepts from the literature were used as decisive criteria in the selection and establishment of the food process configurations and scenarios to be considered in addressing the study's objectives. Chapter 3 deals with the process and economic modelling of the selected food processes. However, the assessment of suggested advanced in-house energy generation from the biomass residues in the mechanised CPO and semi-mechanised/ mechanised CF processing approaches required specific external resources that were unrelated to the other food processes. Thus for clarity in the presentation, the assessment of the referred advanced in-house energy generation for the CPO and CF processes were addressed separately in Chapters 4 and 5 respectively. Nevertheless, the preliminary findings in Chapter 3 were still relevant in addressing the study's objective 1. Chapter 6 discusses the integrated findings from Chapters 3, 4 and 5 (i.e. the overall outcomes of the study). Finally, implications from the study's results and recommendations for feasible application of the findings are given in Chapter 7.

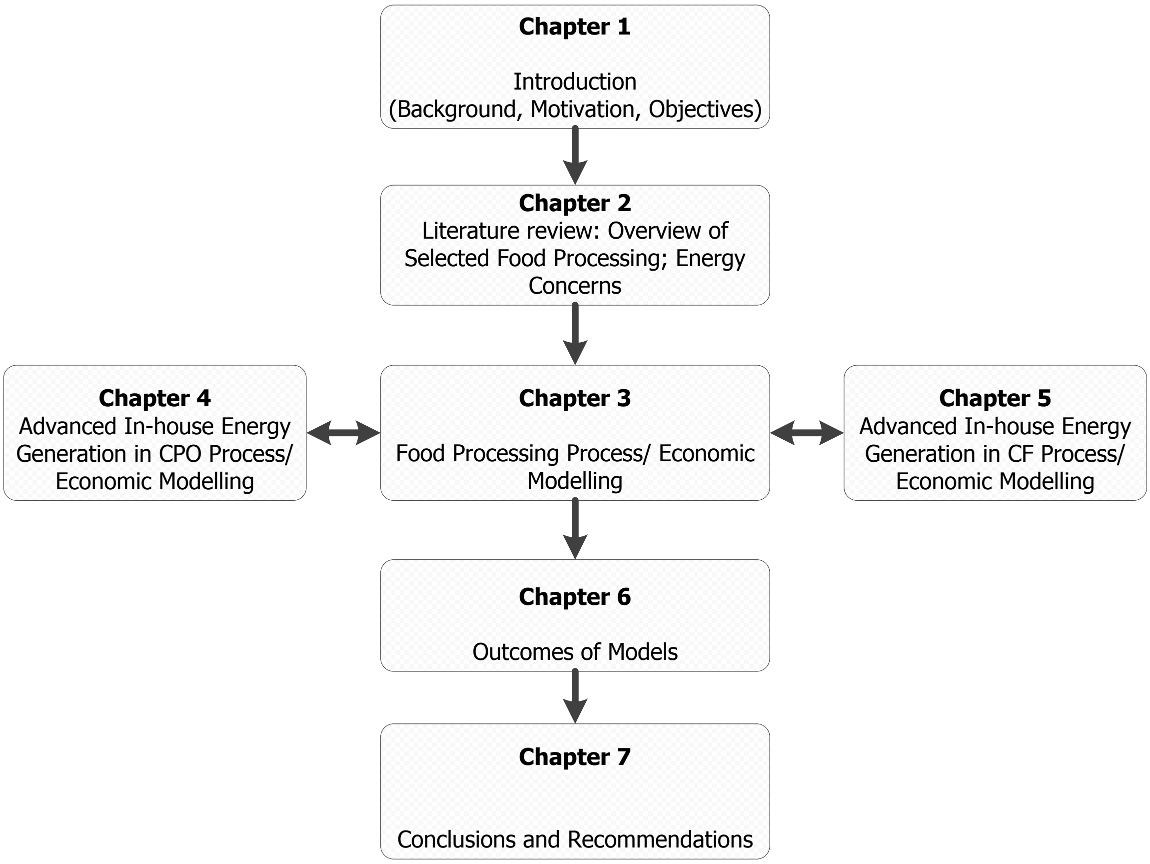


Figure 1-1: Flow diagram of thesis layout

2 LITERATURE REVIEW

2.1 Overview of Selected Food Processes

The farm practices in SSA are dominated by small-scale or subsistence farming which supply over 70% of Africa's food needs and the few large-scale farms are often owned by states or processing companies for their raw material needs (FAO, 2002; IAASTD, 2009). Mismanagement of land, such as poor crop rotation and lack of agro-inputs caused by socio-economic factors such as lack of extension services to provide knowledge on good agronomic practices, and lack of capital to access agro-chemicals and other inputs, leads to an accelerated loss of soil fertility. This promotes the search for new fertile lands, mainly forest and marginal lands (Reij and Smaling, 2008), resulting in longer distances between farms and communal settlements (Rabirou *et al.*, 2012; Toenniessen, 2008). Although little is reported on distribution of farming after shifting cultivation in the general context for SSA, distances between 5 and 10 km from settlements have been reported for Nigeria (Rabirou *et al.*, 2012). In the new scenario of farming at longer distances, availability of transportation for labour, logistics and farm produce, among other factors, is essential for agricultural development. In the context of SSA, poor transportation infrastructure in rural areas imposes challenges on transportation for agro-activities and thus limiting agricultural growth (Torero and Chowdhury, 2005; World Bank, 2008).

In spite of the above circumstances, rural communities still produce major agricultural commodities such as cassava and maize (as shown in Figure 2-1) for mainly local consumption and trading (Chauvin *et al.*, 2012; FAOSTAT, 2013). They are usually processed into intermediate products such cassava and maize four at small-scales using inefficient traditional technologies. Thus, these commodities are of high importance for the local communities and as such, targeting them for improvement necessarily advance self-sustenance and improve standard of living in these communities (Bryceson and Shackleton, 2001).

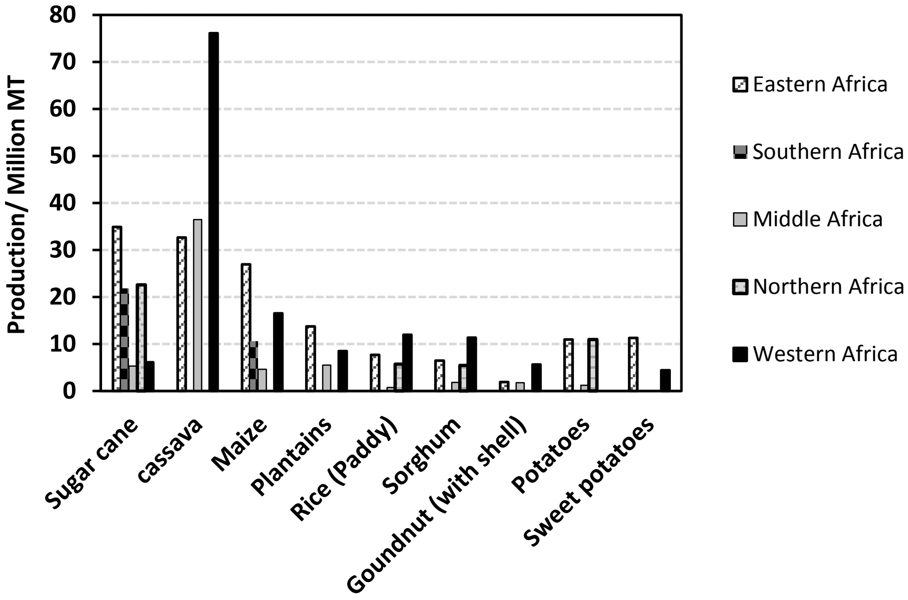


Figure 2-1: Sub-regional productions of representative crops in Africa, 2011 (Data Source: FAOSTAT, (2013))

2.1.1 Selection of Food Products

The cultivation of some crops, their processing into economic valued food products and the products demands are discussed below, to provide an overview of their production and economic potentials in the African context.

2.1.1.1 *Oil Palm Cultivation*

The high global demand of palm oil coupled to its high cultivation potential in tropical Africa has led to the breeding of high-oil yielding varieties, such as the *tenera* variety, with good traits for oil production (FAO, 2002). Successful breeding programs have resulted in high yielding varieties with capability of yielding over 20 tons of bunches/ha annually, with 25% oil content per bunch. Three farming units are characteristic in most of the developed palm oil cultivation regions in West Africa: small-, medium- and large-scale farms. The former usually cover about 7.5 hectares of land, medium-scale about 10 to 500 hectares and the latter covers above 500 hectares of land (FAO, 2002).

2.1.1.2 *Crude Palm Oil Processing*

Palm Oil is at present one of the world's leading sources of vegetable oils. Global production of crude palm oil (CPO) has doubled from 2001 to 2011 (FAO, 2011). Globally, CPO demand is estimated to be increasing by 2.2 million tons annually (USDA, 2009). Among the different uses of CPO, nearly 90% is employed in food applications such as soup-mix, cooking and frying oil, shortenings, margarine and confectionary fats. Non-food uses include soaps and detergents, pharmaceutical products, cosmetics and oleo-chemicals (Shimizu and Desrochers, 2012). CPO is predominantly consumed in developing countries in Asia, Middle East and Africa due to its low-cost compared to other vegetable oils. The demand for CPO in these regions is reported to be on the increase as a result of the continuously growing population in these regions (FAS, 2010).

The upsurge in limited land availability for increasing oil palm cultivation in the high CPO producing Southeast Asian regions, to keep up with the escalating global demands, has heightened interest in developing its African industry (Ofosu-Budu and Sarpong, 2013). Kyei-Baffour and Manu (2008) estimated annual palm oil export potential for West Africa at over 2.6 million tons but only 0.8 million ton was reached. Challenges of poor quality and lower production capacities faced by small-scale rural processors, due to the lower level of technology employed, have been identified as contributors to the low local production (Ofosu-Budu and Sarpong, 2013; Zu *et al.*, 2012). For example in Nigeria, the leading palm oil producer in Africa (Figure 2-2), smallholders or traditional palm oil producers are estimated to make up 80% of the palm oil producing sector, while semi-mechanised processors and mechanised processors constitute 16% and 4% respectively (Ohimian *et al.*, 2012; Ohimain and Izah, 2013).

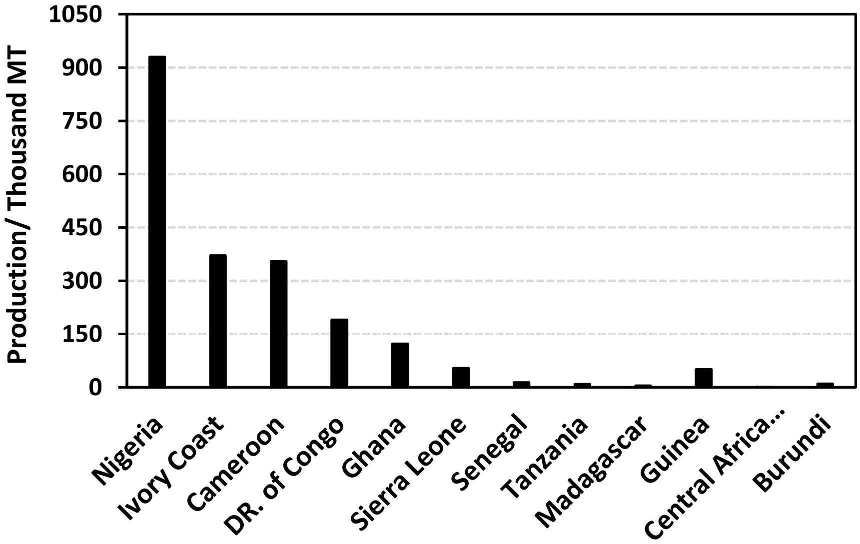


Figure 2-2: 2011 Palm oil productions in selected African countries (Data source: FAOSTAT, (2013))

CPO processing consists of several unit operations with different methods and machinery. The process initiates with harvesting the fruit bunches and terminates with storage of the oil. Based on the processing method used and factors such as throughput and degree of complexity of the machinery, three CPO processing approaches can be identified namely traditional (household scale), semi-mechanised (small-scale) and mechanised (industrial) CPO processes (see descriptions in Figure 2-3, Figure 2-4, Figure 2-5 and Figure 2-6).

Traditional and small-scale facilities commonly have capacities ranging 100 kg to 8000 kg of fresh fruit bunch (FFB) per day, employ crude traditional or semi-mechanised technologies and commonly domestic markets are targeted (FAO, 2002). On the other hand, large- or industrial scale facilities employ fully mechanised units, with capacities ranging 3 tons to 60 tons of FFB per hour, with continuous processing based on raw material availability. Mechanical handling systems such as pumps, pipelines and conveyors are incorporated in these large scale plants and often generate their power and steam demands from process biomass residues (FAO, 2002).

Traditional CPO Process

Two types of palm oil are traditionally produced in most African rural settings namely hard and soft oil. The hard oil solidifies at room temperature (26-27°C), whereas the soft oil does not (Ata, 1974). Small Cooperative Processes that employ semi-mechanised units (combinations of traditional and mechanised units in the processes) is another emerging palm oil process in the rural areas and common in top CPO producing countries such as Nigeria, Ghana and Cameroon (FAO, 2002; Zu *et al.*, 2012). Although small-scale mechanised units of all the production unit operations exist, fully mechanised processes are rare.

Figure 2-3 summarises the traditional soft-oil process. Production of the soft oil begins with manual threshing of the harvested fruit bunches with implements such as the cutlass, to release the fruits from the bunch. The fruits are then washed and boiled. The boiled fruits are pounded in large mortars using pestles, to remove the mesocarp from the nuts. The oil is then released by adding water to the mash and kneading the resulting mixture. The nuts and fibres are separated from the mash using a colander and the residual liquor is allowed to stand for 8-18 hours. This allows the lighter oil to settle on the surface which is skimmed off. Prior to packaging, water in the skimmed oil is removed by evaporation to minimise oxidation to avoid rancidity of the oil (Ata, 1974).

The processing of hard oil differs from that of the soft oil in two basic ways which are: 1) no boiling of the fruits takes place, and 2) the palm fruit is usually fermented prior to extraction as described in the block flow diagram in Figure 2-4. The palm fruits are left in open air for about 3 to 4 days to ferment. In the course of fermenting, the internal heat generated partially cooks the fruit and softens it for further processing, as well as ceasing enzyme activities and further microbial and lipolytic action (Ata, 1974). The fermented fruits are then pounded to separate the mesocarp from the nuts followed by kneading of the mash to release oil. The kneaded mash is mixed with water and left to stand, allowing the lighter oil phase to settle above the water phase for skimming. The residual soup may be boiled to release a little more oil possibly retained in the solids. Usually the skimmed oil is not boiled but a few processors prefer to boil it for a shorter period than in the case of the soft oil, to expel some of the incorporated water (Ata, 1974).

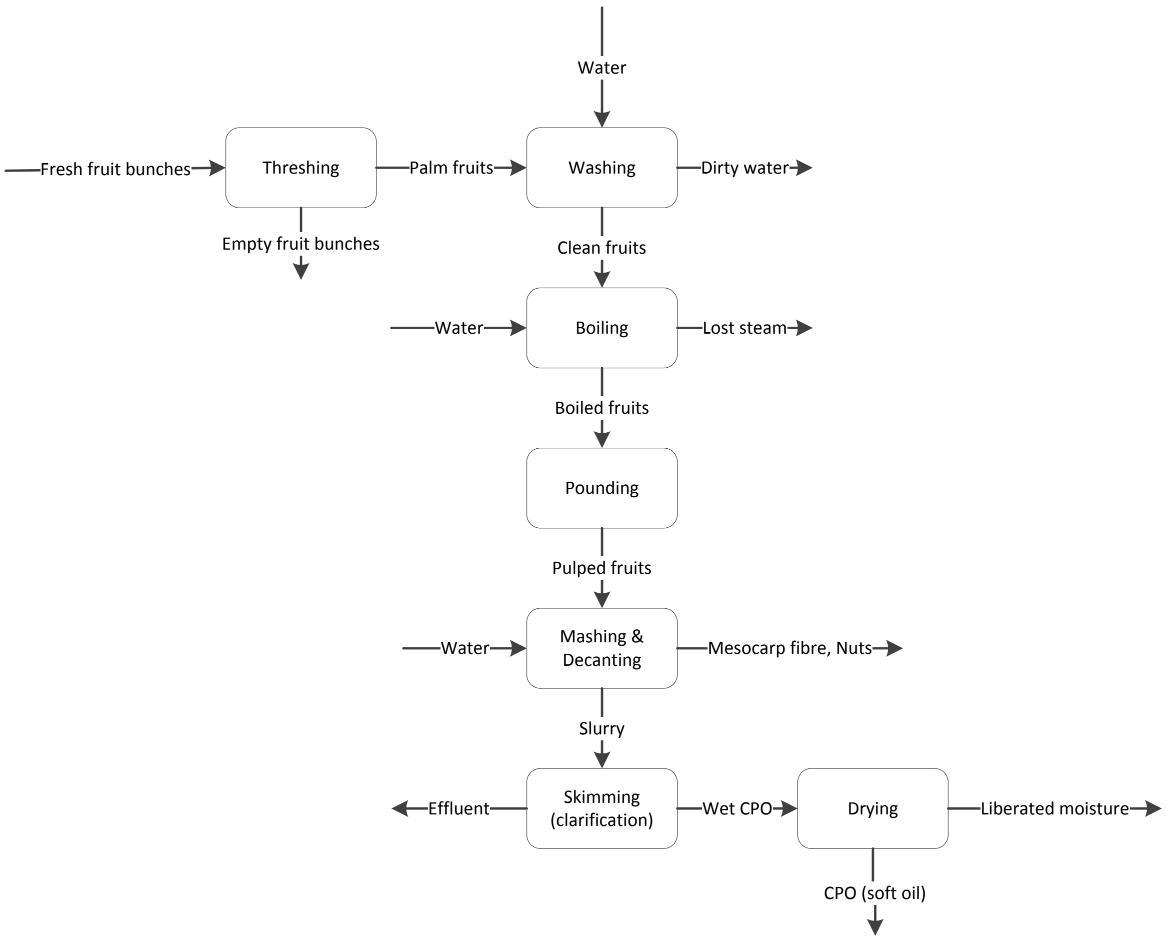


Figure 2-3: Block flow diagram of traditional soft-crude palm oil process

The traditional CPO technology involves indigenous equipment such as mortar and pestles in pounding boiled or fermented fruits, large pots and wooden stirrers as mixers and settling tanks, and ladles or bowls for skimming oil. The entire process takes place in the compound or backyard of the individual processor under a shed, which houses some of the equipment and a clay tripod stove. Occasionally, children or relations assist in the processing.

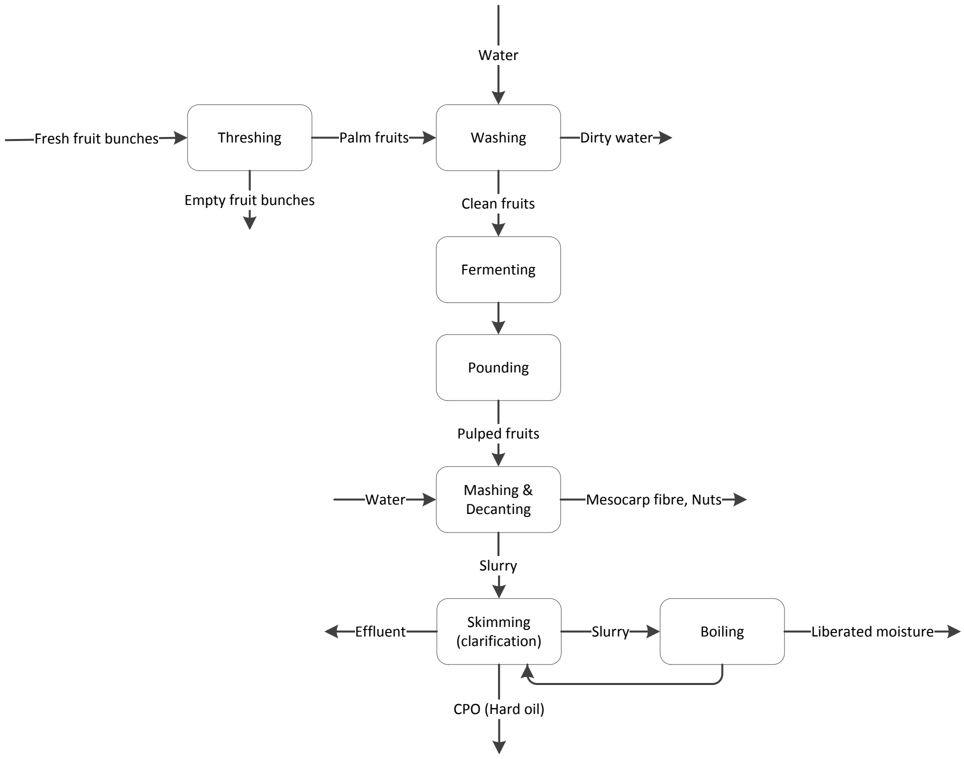


Figure 2-4: Block flow diagram of traditional hard-crude palm oil process

Semi-Mechanised CPO Process

Small-scale semi-mechanised CPO facilities are commonly owned by small cooperatives of between 4 to 12 women (Taiwo *et al.*, 2000; Adjei-Nsiah *et al.*, 2012). Typical throughputs (capacities) of these plants are between few hundred kilograms and 8 tons FFB per day and the final product is mostly for domestic consumption (FAO, 2002). The semi-mechanised process is as shown in Figure 2-5. The semi-mechanised method of production is similar to that of the traditional soft oil production except that the oil is extracted by pressing. Palm fruits are also steamed by in-situ in large containers for about 30 minutes to 1 hour in the case of the semi-mechanised process. The steamed fruits are then pulped mechanically by means of mechanised digesters (steam heated cylindrical vessels equipped with a central shaft with beater arms that rotates and pound the fruits in the process of rotating) and the oil is extracted from the pulp using manual or motorized screw/hydraulic presses. The oil is skimmed and the dense portion is mixed with little water (which is optional). This is then boiled and the lighter oil is skimmed, leaving behind the sludge.

Manual or mechanised screw press and the diesel-powered digester are two major innovations in the processing equipment of the semi-mechanised technology which are both locally constructed/assembled by artisans in some CPO producing nations such as Ghana, Cameroon and Nigeria (FAO, 2002). All the other unit operations of the process employ the traditional technologies.

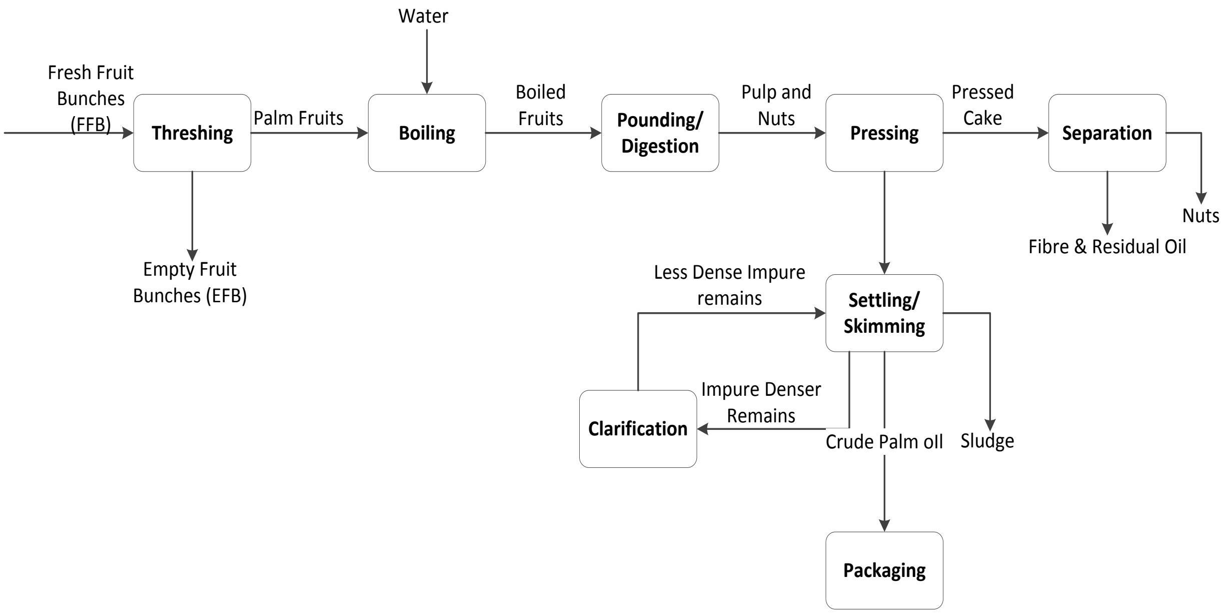


Figure 2-5: Block flow diagram of small-cooperative (semi-mechanised) crude palm oil process

Industrial (mechanised) CPO Process

The industrial scale, fully mechanised process for CPO extraction entails medium or large capacity units, which might be manual or automated. The process could be run in a batch, semi-continuous, or continuous systems. The oil is extracted from consecutive batches of fruits in batch systems. The continuous system is automated with each unit in the oil extraction process feeding into the next. In the semi-continuous system some steps can take longer than others due to possible lapses. Some processing stages (unit operations) are common and basic in nature irrespective of the operability of the machinery employed. A flow diagram for a common, fully mechanised, industrial CPO process is given in Figure 2-6.

The industrial CPO process begins with harvesting the palm fruit bunches, which are then transported by means of trucks to the processing facility's gate. The harvested fruit bunches are weighed with a weighing bridge in large processing facilities or emptied into wooden boxes and weighed by means of a scale. The fruit may be allowed to fully ripen during storage under open sheds, usually for few days for easy threshing in a mechanical thresher.

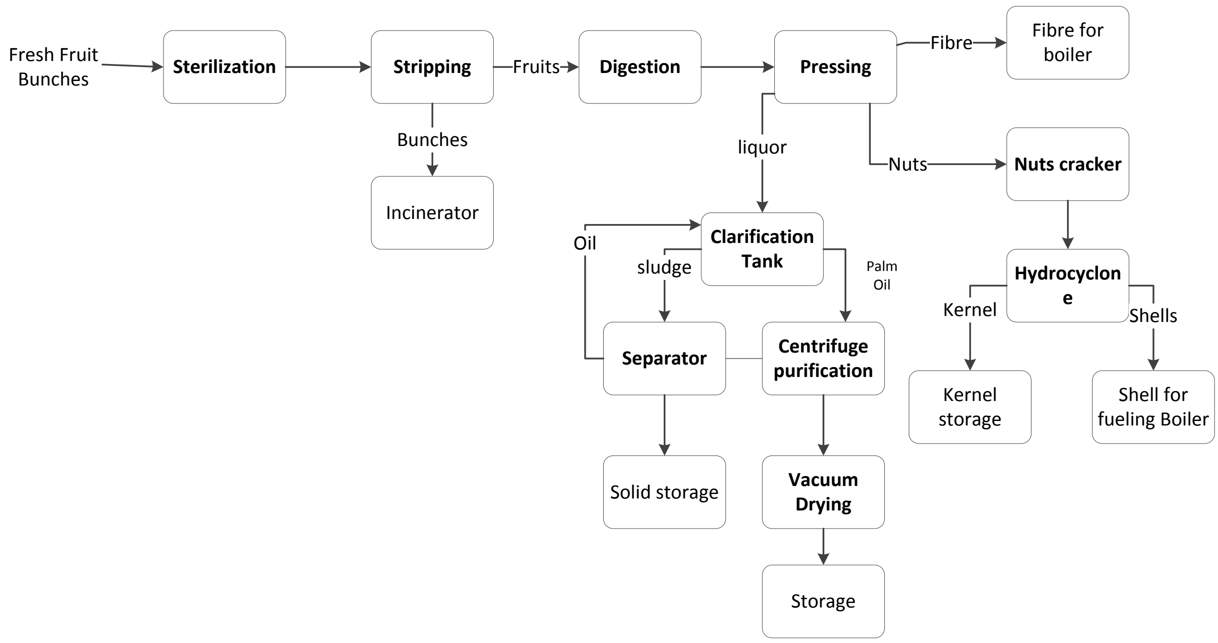


Figure 2-6: Block flow diagram of Industrial crude palm oil process

Threshing is followed by sterilization of the fruits (this may be preceded by the threshing process in some plants) by using heat usually in the form of steam generated in boilers. Sterilization is intended to stop the enzymatic reactions that lead to oxidation, while also disrupting the cells in the mesocarp, allowing for easier oil extraction (FAO, 2002). Wet and dry sterilization are the methods usually employed. The dry method is usually practiced in Southeast Asian production regions, where toasting of the fruits by heating in ambient conditions without water or steam is involved. The wet method entails steaming the fruits in containers or vessels with steam (generated in steam boilers) at 140°C and pressures of 245-313 kPa for about 50 minutes (Mahlia *et al.*, 2001), and is the most employed in African industrial facilities. Sterilisation is followed by digestion, which entails simultaneous crushing of the fruit and partial heating of the pulp to maximize oil extraction. Industrial digesters (steam heated cylindrical vessels equipped with a central shaft and beater arms) then rotate and pound the fruits. Reduction of the viscosity of the oil and complete oil cell disruption is assisted by the steam heating that facilitates the extraction at the pressing unit operation

(FAO, 2002). The pulp is then pressed to break down the oil-containing cells to facilitate the release of the oils by means of motorized screw or hydraulic presses. Fibrous materials, water, cell debris and 'non-oily solids' (NOS) make up the pressed liquor, which is viscous due to the NOS. The liquor is usually clarified in large clarifying tanks by mixing with hot water of about 80^{o}C (to reduce viscosity), screening to remove coarse materials and subsequent heating of the mixture causing the lighter oils to rise to the surface of the mixture. The oil is then skimmed off and further heated in a secondary tank to reduce the moisture to final values in the range of 0.15% - 0.25%. The oil is then filtered to remove impurities followed by qualitative analysis of fat and moisture content and finally pumped to storage tanks (Mahlia *et al.*, 2001; FAO, 2002).

2.1.1.3 *Cassava Cultivation*

Cassava is a perennial crop that can withstand conditions of low nutrient availability and is able to survive drought (Burrell, 2003). It was initially considered as a famine-reserve crop, as it supplied a reliable source of food during drought and food shortage seasons (Nang'ayo *et al.*, 2005). In Africa, cassava production has escalated over the past decade from 101 million tons to 145 million tons in the year 2011, with Nigeria and Democratic Republic of Congo being the leading producers on the continent (see Figure 2-7) (FAOSTAT, 2013). Projections show this trend to continue up to the year 2020 as emerging industrial applications of cassava such as baking flour and ethanol is intensifying national and international concerted efforts to increase yield in most African countries (Nang'ayo *et al.*, 2005; Nweke, 2009). Specifically, the widespread adoption of pest and disease resistant varieties developed by the International Institute of Tropical Agriculture (IITA, 1990) is one of the efforts that have recently been undertaken. Currently, cassava is mostly cultivated in over 40 African countries forming the cassava belt region which spans from Madagascar in the southeast to Cape Verde in the northwest (Nweke, 2009). Majority of these farms are usually owned by peasant farmers on small landholdings (Nang'ayo *et al.*, 2005; Kleih *et al.*, 2013).

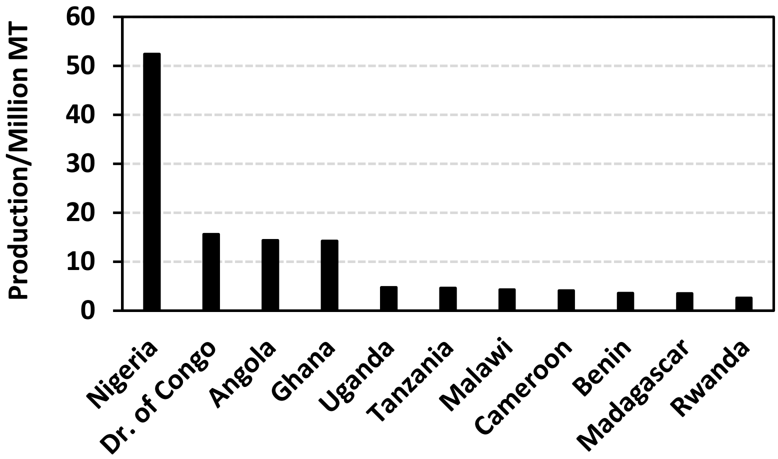


Figure 2-7: 2011 Cassava productions in selected African countries (Data Source: FAOSTAT, (2013))

2.1.1.4 *Cassava Flour Processing*

The processing of cassava flour in some African countries mostly takes place in the rural cassava cultivating areas. The processing varies from country to country resulting in two main types of flour, fermented and unfermented flour that are commonly referred locally as 'lafun' or 'Elubo' in Nigeria (Kuboye, 1985; Uzogara *et al*., 1990), 'Makaka' and 'Mayonla' flour in Malawi (Nyirenda *et al*., 2011) and 'kokonte flour' in Ghana (Quaye *et al*., 2009). Typical uses of cassava flour are in baking and local staple foods.

The lack of standardized processes and process controls, mainly in the traditional process of producing fermented cassava flour, lead to poor reproducibility during operations and inconsistencies in product quality (Iwuoha and Eke, 1996). Reported cases of food poisoning by ingestion of some cassava or related products with high cyanide contents, due to improper processing, have raised health concerns (Nyirenda *et al*., 2011). These challenges faced by the traditional cassava flour processing curtails its potential application in industrial processes such as bread and biscuit baking, and consequently its use remains limited to household level for subsistence needs.

Some attempts to produce cassava flour that meets industrial quality standards by advanced cassava processing belts in West Africa such as Ghana and Nigeria have successfully resulted in high quality cassava flour (HQCF) production (Quaye *et al*., 2009). The HQCF process was developed, according to Falade and Akingbala (2008), by the International Institute for Tropical Agriculture (IITA) in Nigeria as substitute for imported wheat flour in food industries, and replicated in other cassava producing nations. Specifically, HQCF production in 2011 was estimated to be 4000 metric tons in Ghana, which was supplied to the plywood manufacturing and food industries, demonstrating the existence of demand in both food and non-food sectors (Kleih *et al.*, 2013). Among other potential non-food applications are production of adhesives for paperboard manufacture, as an extender for plywood glues and as a source of starch in textiles industries. The formulation of composite flours in bakery products and the production of glucose syrup for the confectionery industry have been also identified as potential food applications (Dziedzoave *et al.*, 2003; Quaye *et al.*, 2009).

The success of producing HQCF is mainly credited to mechanisation of key units in the traditional process. The common mechanised unit operations of the process are washing, grating, pressing, drying and sifting. The degree of adoption of the mechanised units for HQCF in Ghana has been found to be minimal and depended on the production scale. Quaye *et al.* (2009) observed that manual washing was favourable in small-scale processes, while spray washers or rotating drum washers were beneficial only at large scale processing. Mechanised graters such as cylindrical (capacity of 500 kg/hr) and disc (capacity of 200 kg/hr) graters, powered by diesel engines or electric motors, were common to both small and large scale processes (Dziedzoave *et al.*, 2003; Quaye *et al.*, 2009). Mechanised presses comprising the screw press, hydraulic press and the parallel board press are suitable for the pressing process, with the screw and parallel board presses as the most common presses used in rural areas (Quaye *et al.*, 2009). Finally, sifting as essential process step is also carried out by means of a mechanised flour sifter.

Traditional Cassava Flour Process

The production of the fermented flour entails peeling of the root tubers, washing and splitting the tubers into chunks, soaking of the chunks in pots of water or edges of streams for about 3 to 4 days to ferment and soften. The fermented chunks are sun dried for about two days and finally ground and sieved to obtain the flour (Uzogara *et al.*, 1990; Nyirenda *et al.*, 2011). The soaking of the whole root tuber in water to ferment, peeling the fermented tuber, dewatering, sun-drying, milling and sieving to obtain the flour is alternatively adopted (Kuboye, 1985). The production of the unfermented flour by some Southern Africa countries such as Malawi and Zambia, only requires peeling of the tuber, washing, splitting and drying to make the 'makaka' chips which can be pounded or milled to make the 'makaka flour' (Nyirenda *et al.*, 2011).

The traditional process for cassava flour production that use the varieties 'bitter cassava' and 'sweet cassava', faces additional challenges due to their cyanogenic content, although the latter variety exhibits less cyanogen content (< 140 ppm in dry basis) as compared to the former (>140 ppm) (Falade and Akingbala, 2008). The toxicity of cyanogen directly influences the processing of cassava, which is primarily geared towards its reduction below the recommended 10 ppm (FAO/WHO, 1991) and accordingly adapting the processing route to the specific cassava variety. Particular unit operations (stages) in the processing of cassava eliminate or convert the cyanogen into less harmful substances, which are eliminated in subsequent unit operations, as observed for 'sweet' and 'bitter' cassava varieties (Nweke *et al*., 2002). In the case of 'sweet' cassava, the cyanogens are evenly distributed in the tuber, whilst it is mostly concentrated in the peels of the bitter variety and thus eliminated during the peeling unit operation (Falade and Akingbala, 2008). Additionally, at processing unit operations causing loss of cell structure such as grating, the cyanogen induce further reactions with the hydrolytic enzyme linamarase to finally produce hydrogen cyanide (HCN), which is assumed to be completely evaporated during heating unit operations of the process (Bokanga, 1995). Decreases of 98 and 95% of cyanogens after fermentation and grating of cassava, respectively, have been estimated (Akingbala *et al*., 2005). Furthermore, the mode and period of sun-drying directly impacts the degree of elimination of cyanogens, as the enzyme linamarase associated with detoxification is endogenous and active at sun-drying temperatures of 25-40^{o}C (Cooke and Maduagwu, 1978).

Although it has been established that several unit operations (stages) of processing cassava is essential for detoxification and elimination of poisonous cyanogens, challenges such as time constraints, technology constraints and energy needs curtail the complete execution of these activities in the traditional processes. For instance, the absence of mechanised graters in some rural areas results in producing chips from bitter cassava varieties, which might not eliminate the cyanogen content to the acceptable limit (Dziedzoave *et al*., 2003). Also sun-drying unit operation of the processing is solely dependent on weather conditions, which often hinders drying of the cassava chips to required moisture content of 13 to 15% during the wet seasons (FAO, 1997).

High Quality Cassava Flour Process

The processing of cassava roots into High Quality Cassava Flour is summarized in Figure 2-8. The process commences with hand sorting of healthy and matured cassava tubers (10-12 months of maturity) that have no abrasions on the tubers (Dziedzoave *et al.*, 2003). The tubers are peeled either manually (by means of well sharpened stainless steel knife) or mechanically by mechanised peelers in medium or large capacity plants (Quaye *et al.*, 2009). The peeled tubers are then thoroughly washed with clean water for removal of impurities (sand particles and dirt), which could diminish the quality of the product. Grating of the clean tuber is carried out using motorized cassava graters to increase the surface area of the cassava and facilitate downstream processing unit operations (stages), such as the pressing and drying. Dewatering the pulp is mainly done by pressing the pulp to speed up the drying process. The pressing is carried out by packing the pulp into jute sacs and pressing by means of a manual or mechanised screw/hydraulic press for a short period of time (usually less than 6 hours), to avoid fermentation of the grated mash which mars the taste and colour of the flour. The pressing step reduces moisture content and the toxicity of the flour by liberating some of the cyanoglucosides. The resulting pressed cake is then disintegrated to reduce the particle size and then sieved using a rotary sieve to reduce the fibre content before drying (Dziedzove *et al.*, 2003). The dried cassava grits is then milled into fine powdery flour using a disc-attrition or hammer mill. The resulting flour is screened using a motorized flour sifter fitted with a 250 µm screen in order to obtain fine and smooth flour devoid of higher fibre and foreign particles. Finally, the flour is packaged in polypropylene sacks to prevent moisture uptake into the flour during storage. The alternative chipping processing route as shown in Figure 2-8 is only recommended for the sweet cassava variety, as it does not moderate the cyanogen in bitter cassava to below the recommended 10 ppm (Dziedzoave *et al.*, 2003; FAO/WHO, 1991).

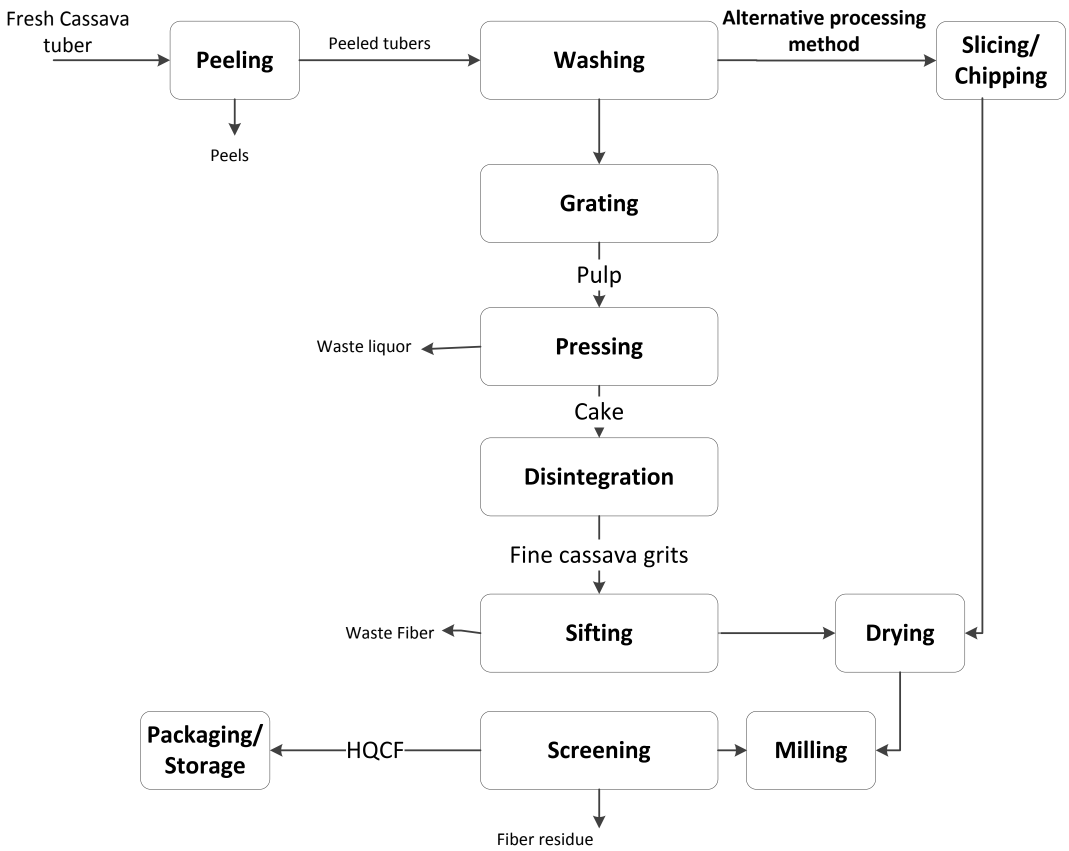


Figure 2-8: Block flow diagram of High Quality Cassava Flour process (redrawn from Dziedzoave et al, 2003)

2.1.1.5 *Maize Cultivation*

Maize cultivation is estimated to be 785 million tons globally with the United States producing 42% and Africa 6.5% of this estimate (FAO, 2007). Its applications is extended to both food and non-food products. In most industrialized countries, maize is significantly used as a raw material for industrial products such as ethanol and livestock feed. It also serves as an important cereal crop in SSA as it is primarily a staple food for the population, with over 95% of its production used as food (IITA, 2014). African maize meals vary depending on the country, although some common forms cut across several countries. For instance porridge is prepared from ground maize in Eastern and Southern Africa, while it is prepared from maize flour in Western Africa. Common to all parts of Africa is its fresh form being boiled or roasted on its cob for snacks.

2.1.1.6 *Maize Processing*

Maize processing into maize flour (MF) in SSA can be divided into upstream and downstream processes. The main upstream post-harvest operations of maize comprise harvesting, stacking, transport from field, storing, shelling and cleaning, with some modification in the sequence of steps for marketing or consumption purposes as indicated in Figure 2-9. The downstream processing depends on the product of interest such as dough, maize meal and maize flour with the latter as the product of interest in this study.

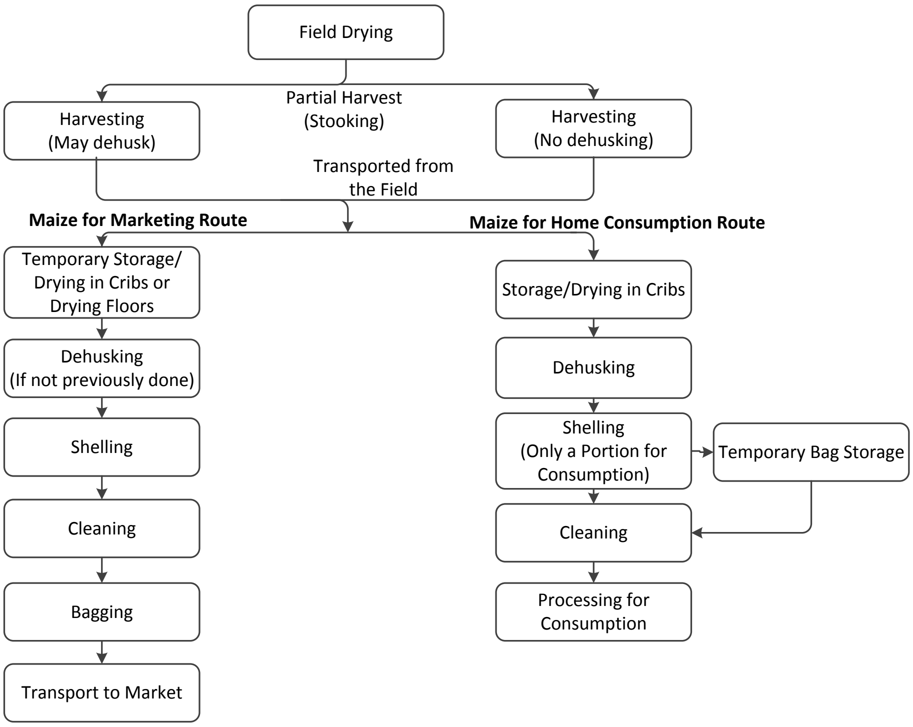


Figure 2-9: Post production operations of maize value chain (modified from FAO, 1997)

Upstream Processing of Maize

In the first upstream step of maize processing, the matured crop is left to dry on the plant until reaching moisture content between 18 and 24% before harvest (FAO, 1992). Harvesting methods often vary based on the farm size, and the cobs are collected from the plant may be dehusked or not dehusked prior to transportation from the field in small and medium sized farms. Cutting the stalks with cobs attached and gathered into stooks in the field, to facilitate field preparation for the next planting season, is the common practice in large farms. The cobs are separated from stalks when dried and may either be heaped temporarily on the field or transported to the storage facilities after dehusking (optional operation). To preserve the quality of maize during storage, the moisture content is reduced to limits of 12-14% by drying at ambient conditions on platforms/storage in cribs or dried at temperature nearly 30°C by mechanical means (FAO, 1997). After adequate drying, the cobs are shelled to free the maize kernels from the cobs. Shelling is often done manually in household processing and mechanised in commercial size facilities. Manual shelling is often attained by beating the cobs placed in sacks or screens for loose grains to fall through and separated from the cobs in the process. Manual shelling is labour intensive and for this reason is the limiting unit operation in the upstream post production process of maize. It is estimated that 2 or 3 adults are required to shell 5 bags a day of 90-kg maize each, while 3 adults can shell about 20 bags of 90-kg maize each during 8 hours of using a hand-operated shelling machine. It has been observed that few large-scale farmers have maize shelling machines attached to tractors or free-standing hand-operated shelling machines (FAO, 1997). The shelled kernels are occasionally cleaned by winnowing with wind currents to separate chaffs and broken cob fragments from the grain, before bagging for marketing or storage.

Downstream Processing to Maize Flour

The stored maize after upstream processing is further processed into valuable foods and industrial products by two main processes, dry and wet milling. Grits, meal and flour are produced by dry milling, while starch and valuable derived products are produced by wet milling. Due to the maize flour as the product of interest, the scope of the present study is limited to the dry milling process summarised in Figure 2-10.

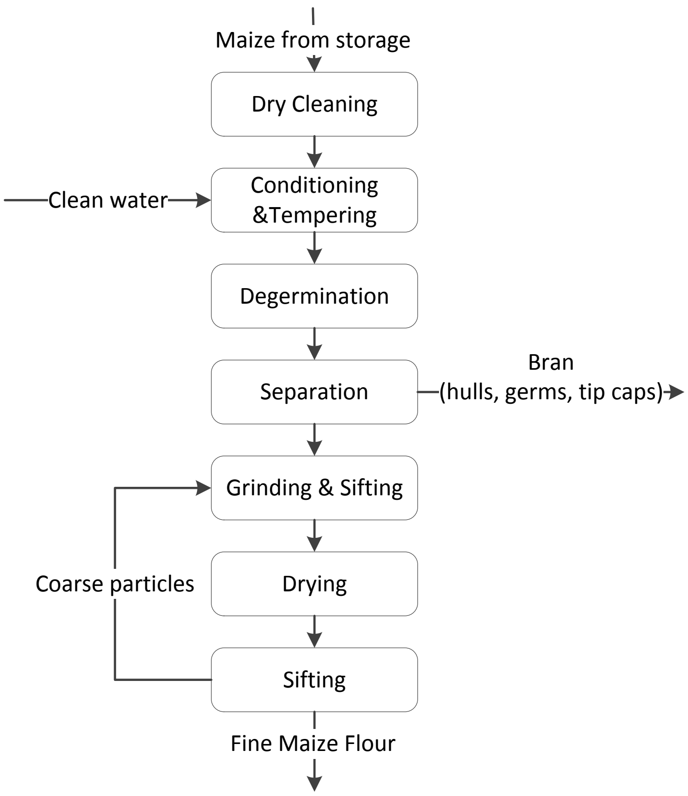


Figure 2-10: Block flow diagram of a typical dry milling maize flour process

Traditional Maize Flour Process

The processing of maize into flour is a laborious and time consuming task performed almost exclusively by women at rural household levels. The process involves hand pounding or grinding of small amounts of dried maize using mortar and pestle or hand grinders respectively. Typical capacities of hand grinders are between 7 and 30 kg. The product is then sieved or winnowed to separate the bran (hulls, tip caps and germ) from the flour (FAO, 1997).

Semi-Mechanised Maize Flour Process

The semi-mechanised process of maize production is similar to the traditional process. The core difference is the introduction of hammer-mills and mechanised units for some unit operations (stages) of the process, such as seed cleaners and dehullers. Hammer-mills are rented to farmers or the milling service is performed by an operator in some rural areas, usually for a fee (FAO, 1997). The grains from storage are cleaned in tanks filled with water to remove impurities such as sand, stones, leaves and pesticide residues in dedicated small-scale semi-mechanised maize flour facilities. The cleaning unit operation is followed by drying to required moisture between 13.5 and 15% by means of a sun dryer or less commonly fuel-fired dryer (Ouaouich, 2004). The dried grains are then sorted or graded with a seed cleaner. Mechanised seed cleaners are inclined vibrating flat screens through which sand and other impurities fall, leaving behind the grains that roll into collectors. Mouldy and spoilt grains can be hand-picked from the sieve during the seed cleaning. Degerming of the clean seeds will remove the hulls (bran), tip-caps and germs of the grains, and is usually performed in a diesel engine–powered degermer (Hounhouigan et al., 2003; Ouaouich, 2004). The degermed grains are then milled in hammer-mills to specific particle sizes by sifting and packaged.

Industrial (mechanised) Maize Flour Process

The industrial process of maize flour production refers to dry milling in a completely mechanised facility. The employed processing approach known as the tempering-degerming process commences with dry cleaning of the grains in a grain separator and destoner, where coarse and fine impurities such as metallic materials, sand and stones are removed. This is followed by conditioning of the maize kernels in an automatic moisture controlling unit by spraying water. Conditioning is then followed by tempering of the kernels, where conditioned grains are allowed to stand for 6 to 12 hours. Further conditioning by adding water to the tempered kernels to soften the hulls or pericarp and is performed prior to degermination process. During degermination, the hulls are removed from the kernels and the dehulled kernels are then broken to loosen the germ. Sifting and aspiration of the resulting mixed-products is undertaken to separate the hulls and germs from the degermed maize (endosperm). The degermed maize is ground and sifted to specific particle sizes. The grinded product is then dried in pneumatic driers with hot air. The dried product is finally sifted to separate course particles from the fine flour product and packaged.

2.2 Energy Concerns

The adoption of mechanised units for some food processes in rural areas of sub-Saharan Africa (SSA) is nominal, primarily due to shortages in availability of affordable modern energy such as electricity and fossil fuels. Additional perceived high risk factors and implications on profit margins are associated with mechanisation by the processors (Kleih *et al.*, 2013; Quaye *et al.*, 2009). It has been suggested that proper coordination and appraisal of the economic feasibility of the rural agro-processing activities will be an effective way of addressing the referred challenges associated with the improved mechanised technologies (Quaye *et al.*, 2009). Furthermore, effective use of renewable energy resources in food processing promises cost reduction in addition to mitigation of the well-known environmental impacts of the use of non-renewable resources (Akinoso *et al.*, 2013). Therefore, the lack of detailed assessment of the impacts of mechanisation and integration of alternative energy sources, limits improving rural food processes.

Process simulation is a cost-effective approach of assessing the technical and economic feasibility of alternative options of energy uses among other factors, and therefore a decision making tool for selection of best option in terms of desirable outputs such as energy efficiency or economic performance. The present work entails process and economic modelling of the food (CPO, CF and MF) processes referred in section 2.1.1, while the integration of the probable renewable energy sources available in SSA is also evaluated.

The total annual primary energy supply in Africa is estimated at 28.2 million GJ (Stecher *et al.*, 2013). This includes 50.5% non-renewable energy sources (coal/peat, oil and natural gas). The 49.5% renewables is made up of 47.6% biomass and the remaining from solar, wind, nuclear and hydro (Stecher *et al.*, 2013). Although renewable biomass usage is significant, it is widely used for cooking and industrial heating applications but minimal in power generation. Out of Africa’s 147 GW power generation capacity (in the year 2011), renewables accounted for only 27.8 GW (19%) including 25.9 GW hydropower, 16 MW wind, 15 MW geothermal and only 7 MW biomass-based power (IRENA, 2011). On the other hand, Africa's estimated technical potentials for power generation from wind, hydro, biomass and geothermal of 436, 211, 300 and 10 GW respectively (IRENA, 2011) indicate the renewable power potentials are under-exploited.

The under-exploitation of the renewable energy resources has been attributed to constraints such as unfavourable national policies, and financial or technical barriers (Karekezi and Ranja, 1997). However, the volatility of crude fuel prices is diverting attention to renewable energy resources. The current energy exploitation in Northern Africa, South Africa and Sub-Saharan Africa (commonly referred as sub regions regarding energy resources) is primarily dependent on their availability to the region and the harnessing benefits. Accordingly, three energy categories for these specific sub-regions have been identified, namely coal dependent (South Africa), oil and gas (Northern Africa) and biomass based in the remaining Sub-Saharan African nations (IEA, 2004). The weight of contribution of the principal energy sources in the African sub regions are given in Figure 2-11.

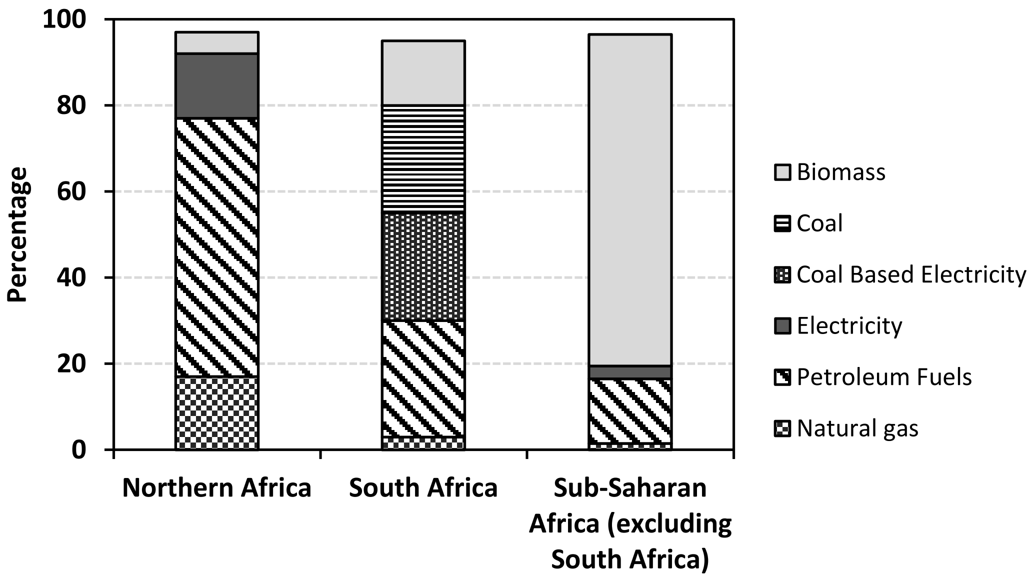


Figure 2-11: Regional energy-mix in Africa, 2001 (redrawn from IEA, 2004)

The following subsections deal with the energy outline considered in the context of SSA, primarily in terms of availability of renewable energy resources and concerns over technologies for their conversion to conventional energy (such as electricity or liquid fuels). Renewable energy sources such as biomass, solar, wind, geothermal, and hydro energy sources were briefly assessed for final selection of the most appropriate types to be applied in the rural food processes under study, as outlined in Figure 2-13.

2.2.1 Accessibility of Electricity in Africa

The International Energy Agency (2004) defines electricity poverty as "when an individual does not have access to at least 120 kWh of electricity per year for lighting and other basic household needs". By this definition, more than half of Africa's population is electricity poor. IEA data indicates that 99.6% of Africa's electricity poverty is concentrated in the Sub-Saharan region, reflecting the great disparities in the different sub regions (IEA, 2004). South Africa and North African nations have the highest installed electricity capacities of 45% and 30%, respectively, with the remaining 24% distributed within sub Saharan Africa (SSA), which harbours over 80% of the continents population (Karekazi and Kimani, 2002). Electricity in Africa is generated mainly from hydro and fossil oils, with the exception of South Africa that generates about 90% of the electricity from coal (IEA, 2004).

Electrification rate (ER), defined as the percentage of the population with access to electricity, in Africa was estimated to be 66.8 and 22.7% in urban and rural areas in 2008, respectively (ARE, 2011). The ER for the continent increased to 68 and 26% in the urban and rural areas in 2012, respectively (WEO, 2014). This suggests that the ER in Africa only improved marginally over four years span. What's more, majority of the referred ER in 2012 was contributed by North Africa, with nearly 100% for both rural and urban areas, as compared to that of SSA at a relatively low of 59 and 16% for the urban and rural areas, respectively (WEO, 2014). The low ER in rural areas of SSA has been seen to contribute to low economic activities and high poverty in these settings (Brew-Hammond and Kemausuor, 2009). Thus improvement in rural livelihood in SSA, where over 60% of the population is located (see Table 2-1) (IFAD, 2011), should effectively address the low access to electricity.

This scenario of unavailability and limited access to electricity currently calls for alternative solutions regarding energy sources. This includes energy options that are locally available, cost-stable, adaptable to small plant facilities and environmentally-benign – renewable energies such as biomass, solar and wind are generally suited to these requirements, as discussed below.

Table 2-1: Electricity accessibility in selected Sub-Saharan African countries

Country	Population		Access to electricity (% of population)		
	Total (millions)	% living in rural areas	Total	Urban	Rural
Benin	9	59.2	22	51	5.5
Ethiopia	79.1	83.3	12	86	2
Kenya	38.5	78.7	13	51.5	3.5
Malawi	13.9	81.7	7.5	34	2.5
Mali	12.2	68.4	13	41	2.5
Senegal	12.4	57.9	46.5	82	19
Uganda	30.9	87.2	47.5	8.5	2.5

Source: World Bank, 2006.

2.2.2 State of Affairs of Renewable Energy in SSA

Aside from the wide-spread use of biomass as fuelwood for combustion in SSA**,** other potential renewable energies are solar, hydropower, wind and geothermal, being pioneered in countries such as Kenya, Namibia, Ghana, Zambia, Cameroon and Mozambique. These countries derive almost all of their renewable energy in the form of electricity from large hydro-plants, except for Kenya where geothermal is the significant source of energy (IEA, 2011a). Studies show electricity from renewable sources in Africa declining from 52.8% in 2000 to 42.1% of the total electricity generated in 2009. Hydropower notably dominated the renewables with contribution of 91.2% of total renewable electricity in 2009, followed by geothermal and biomass with contributions of 6.8% and 1.9%, respectively. On the other hand, wind and solar were not significant contributors to the total renewable electricity (IEA, 2011b).

2.2.2.1 *Biomass Energy*

Biomass in traditional form as wood waste, animal waste, agricultural residues (field and process residues) and charcoal remains the most exploited renewable energy source in SSA, as shown in Figure 2-12. These biomass forms are primarily combusted for cooking and heating needs; however, the low efficiency of traditional cook stoves leads to over exploitation of these resources for relatively lesser gains. Biomass energy contributed an average share of 57.6% of total SSA energy needs (excluding South Africa) in 2008 (IEA, 2011b). The contribution to the total energy demand increased to 80% in 2011, with charcoal supplying about 95% of the urban demand (Belward *et al.*, 2011).

The primary use of charcoal and firewood for heating applications in household cooking has been extended to industrial processes such as brick production, beer brewing, and tobacco curing (Belward *et al.*, 2011; Ndegwa *et al.*, 2011). Annual charcoal production estimates in Africa is over 29 million metric tons (Belward *et al.*, 2011). Ethiopia, as the third largest charcoal-consumer in the world, consumed nearly 89% of the charcoal produced in the late nineties in households centralized in urban areas, and only 4.6% by industries (Belward *et al.*, 2011). Although readily available, traditional biomass usage is detrimental particularly to women and children, due to indoor air pollution from poorly ventilated biofuel cooking stoves and kitchens, which contributes to respiratory illnesses in SSA (Ezzati and Kammen, 2002). Additionally, overdependence on biomass especially wood for charcoal production also encourages deforestation and land degradation, a concern that is rife in some areas such as Lusaka in Zambia, Dar-es-Salaam of Tanzania and Nairobi in Kenya, where high charcoal demand appears to contribute to degradation of the surrounding woodlands and forests (Kantai, 2002).

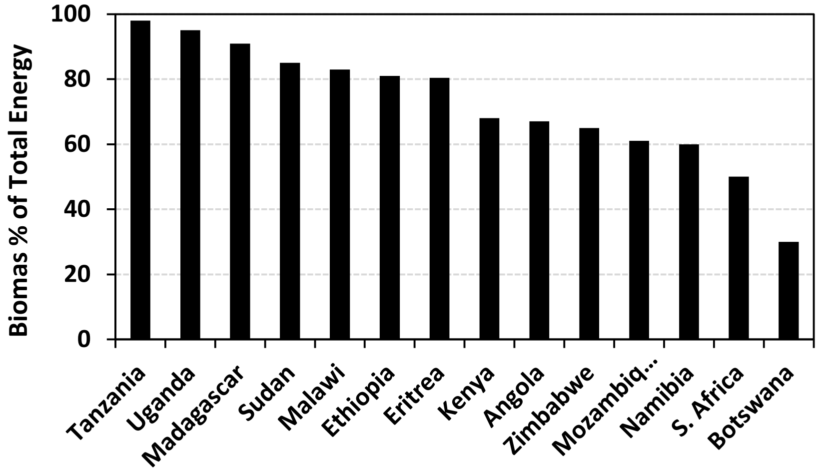


Figure 2-12: Biomass contribution to total energy needs in selected African countries (redrawn from AFREPREN, 2002)

2.2.2.2 *Solar Energy*

Solar insolation in Africa varies notably among sub regions; North and West Africa's average insolation range from 4.7 - 5.6 and 3 - 6.2 kWh/m^2/day, respectively, whilst Southern Africa's radiation varies between 5 and 6 kWh/m^2/day (Ram, 2006.). Africa's technical potentials for power generation from solar using the Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies are estimated to be 539 and 750 GW respectively (IRENA, 2011). The estimated potential for solar power production in Africa, utilizing the

Concentrated Solar Power (CSP) technology, has been suggested to be adequate enough to meet the electricity needs in the continent and yet generate surplus of electricity for exportation (Ram, 2006). Countries such as Namibia, Ghana, Tunisia, Morocco, Kenya and South Africa have made significant progress in promoting the use of solar PV in home systems, but this is limited to high-income households, due to the high purchase cost of the PV systems (Ram, 2006). However, the implementation of solar power technologies in the continent is limited by its high cost and limitations in technical know-how (IRENA, 2011; Ram, 2006).

2.2.2.3 *Wind Energy*

Morocco, Tunisia and Egypt, as pioneers in the use of wind energy in Africa, have already installed wind farms, with Egypt having the highest capacity of about 97% of the total wind power in the continent, corresponding to nearly 550 MW (GWEC, 2011). Morocco and Tunisia's capacities are estimated in 290 MW and 120 MW respectively. Wind power plants expansion is currently under evaluation for the potential benefits exhibited. Nigeria, Ethiopia and Kenya as the countries with the highest interest in implementation, have present intended potential capacities of about 10, 120 and 300 MW respectively (Afrique Avenir, 2010). As seen, wind energy is increasing steadily and expected contribution to the total energy sources in Africa is promising with significance in the near future.

2.2.2.4 *Geothermal Energy*

Geothermal energy, which is primarily natural heat from the interior rocks and water of the earth's crust, is accessed by drilling wells to harness the energy in steams from relatively shallow depths into the earth. The extracted steam is then used in thermal power generation via steam turbines. Estimates show a worldwide geothermal energy potential of 60 GW with 8.1 GW currently accessed, although the concept is relatively new in Africa (Mariita, 2002; Bronicki, 2001). Geothermal potential in Africa is estimated at nearly 9 GW and is prevalent in some parts of the Eastern and Southern sub regions such as Uganda, Eritrea, Tanzania, Zambia, Malawi and Madagascar and highly applicable in Kenya, Ethiopia, Uganda and Tanzania, where sparsely distributed grid connection for electrification exist. Kenya and Ethiopia have implemented geothermal power production of 57 MW and 8.5 MW respectively (Karekezi, 2002).

2.2.2.5 *Hydro Energy*

Estimates indicate Africa's hydro power potential is around 199.8 GW but only about 5% of this has been exploited (UNIDO, 2009). Specifically, the Inga River in the Democratic Republic of Congo has an estimated potential of around 40GW. The remaining significant hydro power potential is distributed among other nations such as Angola, Egypt, Madagascar, Gabon, Mozambique, Zambia, Ethiopia and Cameroon (UNIDO, 2009). Large scale hydropower accounts for about half of the total power supply for 23 African countries. Table 2-2 summarizes the contribution of hydropower to installed electric power in some Southern and East African nations.

Table 2-2: Installed hydro power in some African countries

Country	Installed Capacity (MW)	Hydro power as % of installed Capacity
Mozambique	2,075	100
Uganda	260	98
Zambia	1,786	93
Malawi	242	90
Ethiopia	424	88
Kenya	885	70
Namibia	387	62
Tanzania	655	58
Zimbabwe	1,961	33
Mauritius	425	12
South Africa	38,517	0.01

Source: AFREPREN, 2002.

2.2.3 Renewable Energy Technologies (RETs)

Renewable Energy Technologies (RETs) are energy-providing technologies that utilize renewable energy sources such as solar, hydro, wind, geothermal and biomass for primarily heating and electricity needs (Renewable Energy Association, 2009). Some of the RETs exist in decentralized modules, enabling them to meet diverse but specific needs of different rural areas. The categorization of RETs into two groups is of relevance to the present study: RETs for domestic energy purposes (primarily heating and cooking) and electricity producing RETs. The former RETs produce energy by exploitation of modern/traditional fuels in improved approaches such as cook stoves. Electricity producing RETs can be operated as either a stand-alone (off-grid) system or as a grid-based system through connection to mini-grid or national grid systems (UNCTAD, 2010). The present study of integrating renewable energy in rural food processing call for suitability of specific RETs to the rural settings and various food processes as briefly discussed below.

2.2.3.1 *RETs for Rural Applications*

Suitable RETs for rural applications are typically small scale hydropower, solar, wind and biomass-based energy production, usually in a decentralised or off-grid RET mode of operation (UNCTAD, 2010; Nguyen, 2007). In general, the decentralized RETs have low up-front costs but mostly higher costs per kW installed, as compared to that of centralized technologies (Steger, 2005). However, they still provide the ideal options in rural applications, considering the existing limited success of conventional electrification to dispersed rural communities through national grids (Alazraque, 2008). In addition, the modularity of the decentralized RETs (small scales of kW ranges) makes them ideal in meeting local needs, while situating them close to end users can possible eliminate the high costs of transmission and distribution grids (Nguyen, 2007).

Highlights of the referred decentralised RETs are as follows: Wind energy is primarily employed in either pumping water or electricity generation via wind turbines. Small-scale hydropower plants for electricity generation are available in mini, micro and pico (descending order) sizes and often "run-of-river" types (driven by natural flowing water sources), which subsequently restricts their operation to hydrological conditions such as stream flooding periods and dry seasons (EVN, 1999). Solar photovoltaic (PV) systems operate by converting sunlight into electricity and solar thermal heaters use solar energy to heat stored water or air for heat purposes (Taylor, 2006). In larger power facilities, solar thermal heaters heat fluids such as water, helium, or molten salts used to run a heat engine, that powers a generator for electricity generation (Mills, 2004). Technologies that utilize biomass for rural heating needs are primarily improved cook-stoves and boilers for efficient burning of traditional energy sources or biogas. Solid biomass and biogas can also be used in direct-fired technologies to generate electricity. Table 2-3 below highlights some existing rural energy sources and potential renewable energy technologies for rural purposes.

Table 2-3: Renewable energy applications in rural areas

Rural Energy Service	Existing Off-Grid Rural Energy Sources	Examples of New and Renewable Energy Sources
Cooking (homes, commercial stoves and ovens)	Burning wood, dung, or straw in open fire at about 15 % efficiency	• Improved cooking stoves (fuel wood, crop waste) with efficiencies above 25 % • Biogas from household-scale digesters • Solar cookers
Heating and cooling (crop drying and other agricultural processing, hot water)	Mostly open fire from wood, dung and straw	• Improved heating stoves • Biogas from small- and medium-scale digesters • Solar crop dryers • Solar water heaters • Ice making for food preservation • Fans from small grid renewable systems
Process motive power (small industry)	Diesel engines and generators	• Small electricity grid systems from microhydro, gasifiers, direct combustion and large biodigesters
Water pumping (agriculture and drinking water)	Diesel pumps and generators	• Mechanical wind pumps • Solar PV pumps • Small electricity systems from micro-hydro, gasifiers, direct combustion and bio-digesters

Source: Reproduced from REN21, 2010

2.2.4 Selection of Appropriate RETs for Food Processes

Selection and evaluation of renewable energy technologies (RETs) in Africa is complex as they are still emerging technologies even in developed countries (Torkkeli and Tuominen, 2001; Haung, 2009). It has been suggested by studies that nearly 40% of the implemented RETs in African rural settings fail (Dunmade, 2002), which was attributed to maintenance and repair complexities and poor climate adaptability of the technologies (Barry *et al.*, 2011). The causes of RETs failures has been classified as primary factors, which relate to the adaptability of the technology, and secondary factors, associated to the three branches of sustainability namely socio-political, environmental and economic sustainability (Dunmade, 2002).

Sustainability is a broad concept that relies on the implications of utilizing existing resources without damaging the ecosystem (Er *et al.*, 2011). Therefore by extension, its adherence in choosing suitable RETs is challenging considering the diverse renewable energies and technology ranges (Sathaye *et al.*, 2011). However, economic assessment has been embraced as common sustainability criteria for all RETs and thus such perspective was adopted in the present study. Section 4.2.1.1 (CHP Technology Selection for the Solid Residues to In-House Energy Process) and section 4.2.1.2 (CHP Technology Selection for the POME to In-house Energy Process), exemplify the criteria for the specific study cases in this work.

Sorensen (1991) suggested that when introducing renewable energies into a society's energy supplies, attention on how the society uses energy and the conversion efficiencies of the energy technologies must be considered. The selection of RETs for the food processes under study was thus subjected to a developed conservative framework based on Sorensen's criteria. Figure 2-13 shows the developed framework for selection of potential RETs for the food processes under study.

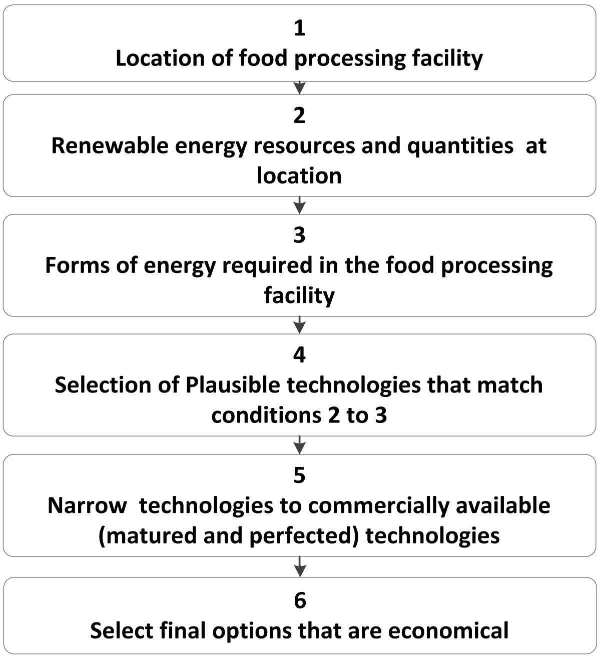


Figure 2-13: Criteria for selection of Renewable Energy Technologies for applications in rural food processes

2.2.5 Energy Concerns in Food Processing

Rural based food processing involves fundamental transformation activities such as milling, fermenting and drying, as described in section 2.1.1, with their conventional energy dominated by manual energy and biomass sources as shown in Table 2-4 and Table 2-5.

Jekayinfa and Bamgboye (2008) investigated trends of energy demand in some industrial food processing plants in Nigeria and concluded that the major energy sources in those processing plants were electricity, crude fuel oils and gas, with a consumption pattern depending on the available energy and scale of production. It was also noted that production cost per unit output decreases as the plant capacity increases, as is typical for economies of scale in industrial manufacturing. However, the opposite was observed in plants that were highly dependent on electric power from national grids. These grids are characterized by frequent interruptions that led to low product per unit time and thus high energy cost per unit product (Jekayinfa and Bamgboye, 2008).

Table 2-4: Energy demands in selected rural food enterprises

Enterprise	Highlights
Beer Brewing	25% of fuel wood in Ouagadougou; 1 kg wood/1 litre beer
Bakeries	Wood is 25% bread production costs in Kenya; 0.8-1.5 kg wood/1 kg bread
Fish smoking	40000 tons of wood/year in Mopti, Mali; 1.5-12 Kg wood/kg smoked fish; fuel is 40% of processing costs.
Palm oil processing	Arduous- lifting and moving heavy containers of liquids; 0.43 kg wood/ 1 litre oil; 55% of income of female households in Cameroon
Cassava processing	1 kg wood/ 4kg cassava

Source: Reddy, Williams and Johansson, 1997.

Table 2-5: Sources of some African countries cooking fuel (% of fuels used)

Country	Firewood	Gas, Kerosene	Charcoal	Electricity	Others
Central African Republic	100	0	0	0	0
Guinea	99	0	1	0	0
Gambia	97	1	1	0	1
Mali	97	0	0	0	2
Tanzania	96	0	3	0	0
Madagascar	94	0	5	0	0
Uganda	94	2	4	0	0
Kenya	93	2	4	0	0
Ghana	92	1	7	0.1	0.2
Burkina Faso	91	1	1	0	7
Niger	90	1	0	0	9
Cote d'Ivoire	89	1	2	0	8
Zambia	89	0	9	1	1
Botswana	85.7	14.1	0	0.03	0
Senegal	84	2	12	0	2
South Africa	49	23	5	21	2
Djibouti	44	48	5	1	2

Source: World Bank, 2000.

2.2.6 Potential Renewable Energies in the Selected Food Processes

Considering that the potential plant location encompasses any of the food or crop producing nations in SSA, the most probable initial factor to be applied in selecting the potential renewable energy for the food processes will be the dominant renewable energy resource common to the entire sub-Saharan Africa region. Specifically as established in section 2.2.2 (State of Affairs of Renewable Energy in SSA), geothermal, wind and hydro resources are specific to certain geographical locations and the latter two are subject to seasonal conditions thus with unreliability for regular load demands such as in the industrial food facilities considered under this study. On the other hand, enormous biomass and solar resources are available across SSA. In addition, some solar and biomass technologies such as solar PV and direct-combustion are already commercially available (that is matured and well-established technologies) and well-suited for rural applications (REN21, 2010; IRENA, 2012a; 2012b).

2.2.6.1 *Solar Potential*

Solar technologies utilize direct sun energy to generate energy for facilities such as buildings and industrial processes. Considering the high potential of the solar resource, solar technologies are not constrained by unreliability of the referred resource, but rather factors such as low efficiencies, perceived economic risks and specific site conditions. Current solar technologies are photovoltaic (PV) and thermal-based (power generation and heat applications). The former is well established and commercially available technology, whilst the latter still in development or demonstration phase, directed towards reliability in operation of such facilities (Arvisu *et al.*, 2011). Although PV technologies are commercially available and are rapidly achieving promising cost benefits, technical and economic factors such as low conversion efficiency between 3 and 42.5% (Ferry and Monoian, 2012), complex technical know-how and high cost of investments limits its immediate commercial application in most developing SSA rural areas (Arvisu *et al.*, 2011; Ram, 2006). Thus, solar technologies were not considered as integration options in the food processes under study.

2.2.6.2 *Biomass Potential*

Biomass is ranked fourth in global energy resources and is estimated that 14% of the total energy needs is provided by this resource. Approximately 35% of the energy used in developing countries is supplied by biomass and commonly the single accessible and affordable source of energy in the developing rural areas (Hall *et al.*, 1992). As stated in section 2.2.5 (Energy Concerns in Food Processing), biomass stands as the main source of energy in rural food processes in SSA and basically used as heating fuel by combustion. Alternative mechanical, thermo-chemical and biological approaches for converting biomass to energies such as synthetic gas, bio-oil and briquettes (as shown in Figure 2-14) are rare in rural areas.

Over 90% of existing biomass power technologies globally employ combustion, a mature and commercially available technology existing in capacities 4 to 100 MW (US EPA, 2007). Combustion to power involves steam generation from biomass fuelled boilers which is fed to steam turbines that converts its thermal energy to mechanical power required by a generator to produce the electricity (IRENA, 2012a). Gasification or gas turbine technology is another proven promising thermo-chemical route with improved environmental and economic performance (IRENA, 2012a). Gasification is conducted to convert biomass to synthetic gas (Syngas) through the use of gasifiers. Syngas mainly contains carbon monoxide and hydrogen that can be combusted in an aero-derivative gas turbine, which powers a generator for power production.

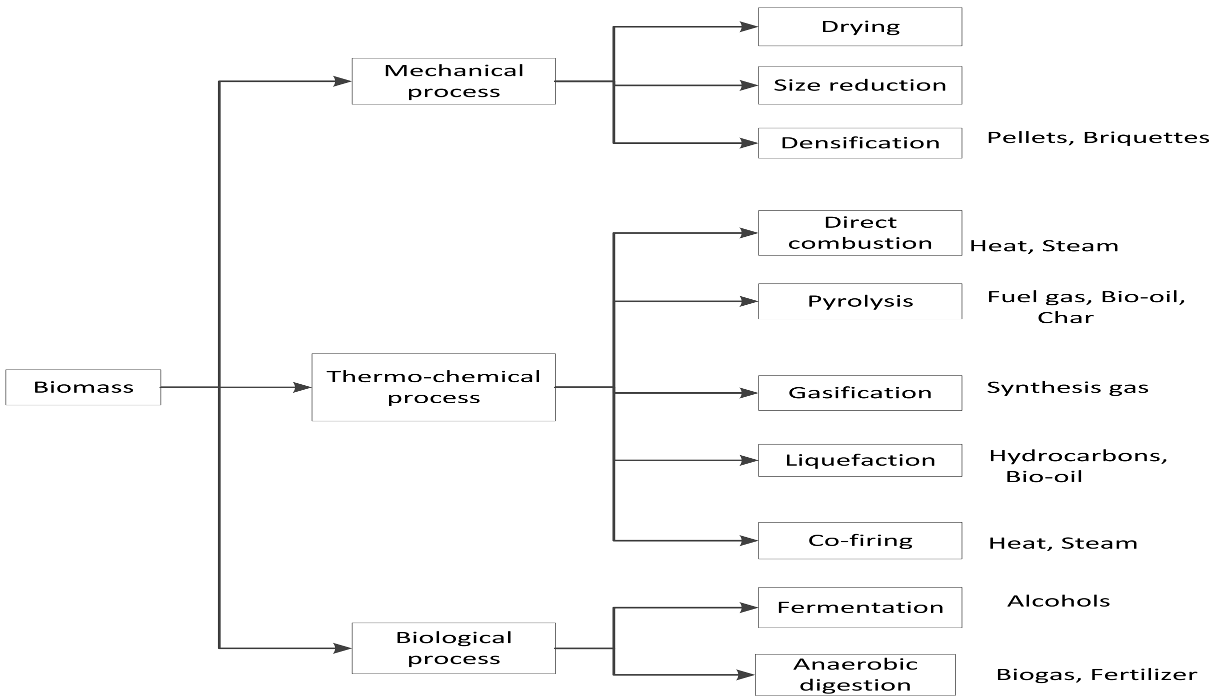


Figure 2-14: Alternative routes of biomass conversion to energy (redrawn from Kerdsuwan and Laohalidanond, 2011)

Biological process for biofuels production can be broadly grouped under first and second generation routes according to the biomass feedstock employed (Food-based crop for first generation and non-based crops and residues for second generation biofuels) in the energy production. The first generation route involves transformation of conventional agricultural crops such as sugarcane juice and edible grains such as maize and wheat through fermentation to ethanol or anaerobic digestion to biogas. However, competition with food and land use which together result in negative impacts on society regarding volatility in food prices and limitation in food availability make this technology unsustainable in the long term (Youngs and Sommerville, 2014).

Second generation biofuels are intended to fill the gaps faced by the first generation biofuels through the use of lignocellulosic biomass such as woody plants, dedicated energy crops, agricultural and food processing residues, among others. Lignocellulosic ethanol has been noted to be the most promising second generation biofuel and is currently under large-scale production in six plants in developed economies of United States, Canada and Europe (Dale, 2015). However, the use of second generation feedstock for ethanol production requires a pretreatment step as prerequisite to overcome recalcitrance in the plant materials and further enzymatic hydrolysis and fermentation (Pedersen and Meyer, 2010), which makes the process more sophisticated and energy intensive and often impractical for African rural areas with low technical know-how.

Biomass wastes generated in the food processes under study such as mesocarp-fibre (mf) and empty fruit bunch (efb) in the CPO process, and cassava peels in the cassava flour process, represent a potential source of renewable energy that can be used to meet the required process energy such as heat, electricity, and biogas. Anaerobic digestion and direct combustion are simple and affordable options that can be employed for in-house energy generation and integration in the African rural food processing and therefore considered for evaluation in this study (Wang, 2009). Direct combustion of CPO solid residues and anaerobic digestion (AD) of Palm Oil Mill Effluent (POME) are discussed in Chapter 4 and AD/gasification of cassava peels are detailed in Chapter 5.

3 FOOD PROCESS MODELLING

Summary

The economic benefits of the mechanisation of food processing, and strategic in-house energy generation from process biomass residues, in crude palm oil (CPO), cassava flour (CF) and maize flour (MF) processing were assessed. This was achieved through developing theoretical process and economic models for the referred foods processing and potential in-house energy generation processes. The process models were developed based on technical data and conservative assumptions from literature.

Traditional, semi-mechanised and mechanised processes represented different levels of mechanisation in food processing. For each of the mechanisation approaches, process and economic models for Base-case (B/C) scenarios entailing the present processing approaches and conventional energy sources were developed. Corresponding process and economic models of Improved-Case (I/C) scenarios, augmented with in-house energy generation from process residues, were also developed. However, the advanced in-house energy integration schemes in the I/C scenarios for the mechanised CPO, semi- and mechanised CF processes required extensive process modelling in Aspen Plus® simulation software, as addressed in Chapters 4 and 5. Thus, only the result of the energy demand and energy-mix of the B/C scenarios are given in this Chapter.

The result of the process models for the B/C scenarios revealed the process energy intensities ranged between 6.00–37.06 MJ/kg, 1.96–4.13 MJ/kg and 0.17–1.36 MJ/kg for the CPO, CF and MF production processes respectively. Furthermore, mechanisation of the processes was associated with higher modern energy (electricity and diesel) demands, which corroborates with trends in literature. In addition, mechanisation resulted in energy saving benefits in the cassava flour process, higher energy demands in the maize flour process and no consistent trend on energy demands in the CPO process. Major avenues for renewable energy integration were the drying operations in the semi-mechanised and mechanised CF processes, and the milling/shelling and drying operations in the semi-mechanised and mechanised MF processes, respectively. On the other hand, minimal opportunities existed for renewable energy integration in the CPO process as most of the process energy was renewable biomass based (from the residues or wood fuel) - although potentials exist for substitution of externally sourced wood fuel and electricity in the

traditional and mechanised processes with in-house biomass residues. Detailed energy and economic performances of the food process models are discussed in Chapter 6.

3.1 Introduction

The demand for crude palm oil (CPO), cassava flour (CF) and maize flour (MF) has grown substantially with the emergence of their diverse applications in both food and non-food industries (USDA, 2009; Nang'ayo *et al*., 2005; FAO, 2007). This has led to intensification of national and international efforts to increase the cultivation of oil palm, cassava and maize in African producing nations to meet the corresponding increase in feedstock demand in the associated food processes (Ofosu-Budu and Sarpong, 2013; Nang'ayo *et al*., 2005; Thorne *et al*., 2002). Although these efforts are yielding results, the processing of these crops to the food end-products have been relegated to traditional processors who employ inefficient traditional (rudimentary and indigenous) technologies, leading to low production and low quality of the products (Aworh, 2008; Zu *et al*., 2012; FAO, 1997).

Mechanisation of the traditional processes has been shown to address the associated challenges. However, concerns of profitability uncertainties and lack of reliable and affordable modern energy (electricity and diesel) to power the mechanised technologies have been cited as major reasons for the limitations in adopting the mechanisation technologies (Kleih *et al*., 2013; FAO, 2012; Quaye *et al*., 2009). Hence, based on the level or extent of mechanisation of the process units, three processing approaches could be identified for the referred foods processing: the common processing approach being the traditional process that employs traditional technologies and often at household-scale, the semi-mechanised process in which combinations of traditional and mechanised technologies are considered and often at small-scale capacities, and the less frequently implemented, fully-mechanised process, which utilises mechanisation technologies and usually at industrial scale capacity (Aworh, 2008; Ouaouich, 2004; Dziedzoave *et al*., 2003; FAO, 2002).

On the other hand, biomass residues from the referred food processes stand as potential renewable energy resources that could be converted by proven renewable energy technologies for the energy demands of the food processes (in-house energy generation) (Wang, 2009). Consequently, conversion of these residues to in-house energy forms has been studied. Combustion of solid residues (mesocarp fibre, empty fruit bunch and palm kernel shells) and anaerobic digestion of the palm oil mill effluents (POME) to the CPO mill's process energies (steam, hot water and electricity) (Panapanaan, 2009; Yusoff, 2006; Yeoh, 2004), gasification of cassava peels residue to electricity/dryer fuel in cassava flour processing and anaerobic digestion of cassava peels to biogas (Serpagli *et al.*, 2010a; 2010b; Adelekan, 2012), and maize cobs usage as dryer fuel in maize processing (Belonio *et al.*, 2012) have been investigated. However, the lack of a thorough technical and economic feasibility assessment of the in-house energy generation from the process biomass residues in the referred African foods processing industries remains a barrier for the implementation of such food and energy integration ventures by investors. This could be due to the capital intensive nature of pilot scale feasibility study approaches.

In this study, the energy and economic impacts of mechanisation, and the technical and economic feasibility of in-house energy integration in crude palm oil (CPO), cassava flour (CF) and maize flour (MF) processing were assessed through developing process and economic models based on available technical data and conservative assumptions from related literature. The outcomes of the models were used to ascertain the practicality and economic benefit of mechanisation and in-house energy integration in the African food processing context.

3.2 Methodology

3.2.1 Conceptual Approach to Developing the Process and Economic Models for the Food Processes

The process and economic modelling approach comprised the food process modelling, in-house energy from residues process modelling, and economic modelling of the integrated food and in-house energy processes as summarised in Figure 3-1. Traditional, semi-mechanised and mechanised processes were the considered mechanisation approaches for each food process. For each referred mechanisation approach, a Base-Case (B/C) scenario entailing the present processing approaches and conventional energy sources was considered. Thus comparing the outcomes of the models for the Base-Case scenarios of the traditional, semi-mechanised and mechanised levels of each food process would address the study’s objective 1 aimed at determining the impact of mechanisation on the energy demands of the process, in addition to identifying potential avenues for renewable energy integration into the processes. To achieve the study’s specific objectives 2 and 3 directed at determining the potential and economic impact of in-house energy generation from the food process residues, corresponding Improved-Case (I/C) scenarios (for each Base-Case scenario) which comprised suggested in-house energy generation from the process residues were also considered. Thus, comparing the outcomes of the models for the B/C scenarios of each food process to their respective I/C scenarios provides the basis for evaluating the potential and economic impacts of incorporating the in-house energy generation from the process residues into the food processes.

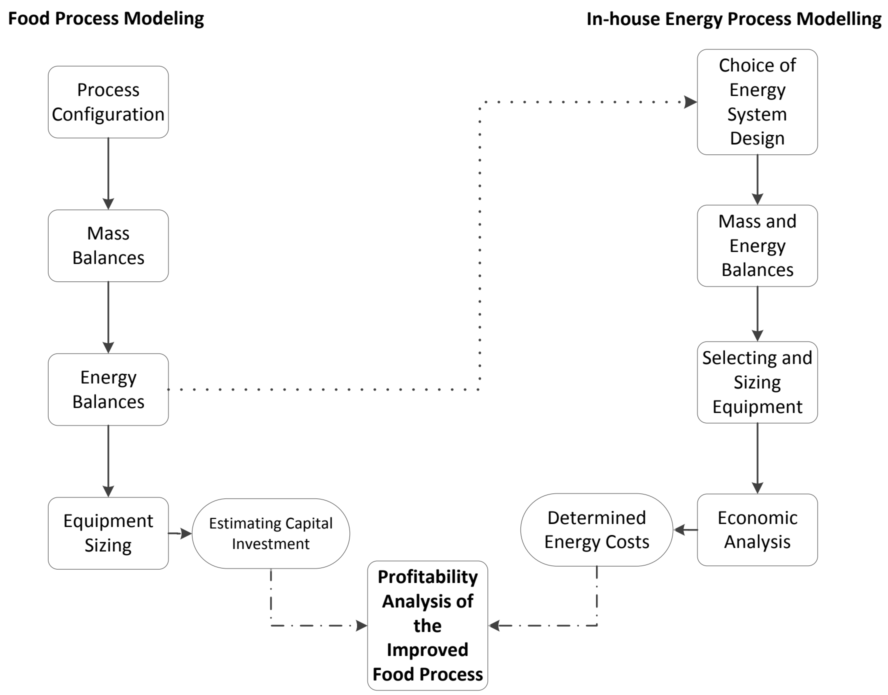


Figure 3-1: Conceptual design and approach to modelling food processes

3.2.2 General Approach to the Process and Economic Modelling

For the food process modelling, available technical data information from literature was used to develop the process configurations, followed by mass and energy balances, all of which were performed in Microsoft Excel 2010 (Microsoft Corp, Redmond WA, USA). The outcomes from the mass and energy balances and information from applicable equipment manufacturers were considered in selection and sizing of the process equipment such as dryers, mills among others from available options. Costs of the selected equipment (sourced from literature or manufacturer's quote) were then used for estimation of the Fixed Capital Investment (FCI) of the various food processing scenarios. Appropriate Renewable Energy Technologies (RETs), based on the form and amount of energy requirement (obtained from the energy balances in the food process models) and quantities/forms of process biomass residues generated (obtained from the material balances in the food process models), were selected for the in-house energy integration. Process modelling of advanced in-house energy processes was performed following a similar path to the aforementioned food process modelling path (as shown in Figure 3-1). Finally, economic models of the modelled energy processes was performed in Microsoft Excel aimed at estimating the lifelike energy prices required for economic viability of the in-house energy processes. The obtained lifelike prices were applied in estimating the working capital (WC) for the Improved-Case (I/C) scenarios of the food processes. The estimated WC and FCI were then used to assess the economic viability of the I/C scenarios of the food processes. For the economic modelling of the Base-Case scenarios of the food processes, the costs of process energy was sourced directly from available cost data or estimated from related literature.

3.2.2.1 *Sectioning of Present Work*

The feasibility assessment of suggested advanced in-house energy integration in the I/C scenarios of the semi-mechanised/mechanised cassava flour mills (process electricity/dryer fuel from cassava peels residue), and the mechanised CPO mill (process electricity/thermal energies from solid residues or Palm Oil Mill Effluent) (see section 3.2.3.1) required extensive resources and process modelling in Aspen Plus®. Thus the assessments of the referred advanced energy processes were addressed separately in Chapters 4 and 5. Therefore, only the food process models are detailed in this Chapter with emphasis on the process energy forms (energy-mix) and energy intensities (process energy demands in MJ/kg product) for the Base-Case (B/C) scenarios to assess the impact of mechanisation on the energy demands of the food processes and potential avenues for renewable energy integration in the processes (as outlined in the study’s objective 1). The detailed energy and economic performances of all the modelled food processes (B/C and I/C scenarios) are discussed in Chapter 6 (OUTCOMES OF MODELLED FOOD PROCESSES).

3.2.3 Food Processes Modelling Basis and Assumptions

The assumptions and basis in developing the food process models are summarised in Table 3-1and applicable equations and additional data used in the mass balances are summarised in Table 3-2. The food process modelling commenced with the establishment of process configurations, dependent on the mechanisation approaches (traditional, semi-mechanised and mechanised processes), as described in literature (see sections 2.1.1.2; 2.1.1.4; 2.1.1.6). In cases where literature was not available, assumptions based on best practice approach were made from related literature or field observations.

The parameters considered in the establishment of the configurations were production capacities [which were dependent on the organisational levels (house-hold, small-scale or industrial level) as noted from literature], forms of energy, and mass conversion and energy efficiencies of the process equipment. Production capacities (kg product/day or week) are dependent on availability of raw materials therefore seasonality of the raw materials was considered in specifying production capacities in the cases of inadequate literature. In the mass balance calculations, composition of feedstock (weight percent, wt%), mass conversion efficiencies of the process equipment (kg product/kg feedstock) and typical process conditions were adopted from related literature. Likewise in the energy balance calculations, energy efficiencies of the process equipment or conservative assumptions based on the energy forms were considered as outlined in section 3.2.4 (Estimation of the Energy Requirements for the Food Processes Developed Process flow sheets showing the process descriptions and various energy forms for the traditional, semi-mechanised and mechanised food processes are provided under section 3.3 (Results and Discussion). Considerations which informed the assumptions in the food process models are further discussed in the subsections below.

3.2.3.1 *General Assumptions Considered in Developing the Food Process Models*

In the traditional processing approaches for the referred food processes under this study, the assumption of household processors having two units of small-scale farms cultivated alternately every year was to ensure year round availability of raw material for processing. Also, the lower energy efficiencies of tripod stoves of 15% (REN21, 2010) in the B/C scenarios imply high energy losses and consequently higher fuel consumption. Hence the suggested improved cook-stove with efficiency of 30% (Lau *et al.*, 2013) for the I/C to reduce fuel demands and improve revenue from sale of saved residues for energy purposes. Specific assumptions for each level of mechanisation for the referred food processes are detailed below.

Crude Palm Oil (CPO) Processing

Semi-mechanised CPO Process

A mechanised digester with diesel engine prime mover, and separate hand-operated screw press was selected for the semi-mechanised B/C scenario as it was the most common in use (Zu *et al.*, 2012). For the I/C scenario, a motorized digester-press which integrates the unit operations of digestion and pressing resulting in higher CPO yield was adopted (FAO, 2002).

Table 3-1: Summary of basis and assumptions in developing the food process models

Food process	Mechanised/Organisational level	Source of Feedstock	Production Capacity	Energy Integration Schemes	References
Crude Palm Oil	Traditional (Household scale)	7.5 ha farms (2 units) cultivated alternately [1]; yields of 20.08 tons FFB/ha/yr [2]	96.91 kg /day (5 days/week (260 days/year))	B/C. Tripod stove (efficiency 15%) [3]; Wood fuel [4]	[1]FAO, 2002; [2]Yusoff, 2006; [3]REN21,2010; [4]Reddy et al., 1997; [5]Lau et al, 2010
				I/C - Improved cook-stove (Efficiency of 30%) [5];solid residues (MF, PKS, EFB) as fuel	
	Semi-mechanised (Small - cooperative group) [6]	Purchased from neighbouring farmers	B/C - 1056 kg /day (5 days/week (260 days/year))	B/C - Tripod stove (efficiency 15%) [3]; mechanised digester/ hand-operated screw press [7]	[6]Adjei-Nsiah et al., 2012; [7]Zu et al, 2012
			I/C - 1600 kg/day (5 days/week (260 days/year))	I/C - Improved cook-stove (Efficiency 30%) [5]; motorized digester-press [7]	
	Mechanised (Industrial Scale capacity of 13 tons FFB/hr capacity) [8]	Mostly from neighbouring farmers; buffer from facilities own large scale farm of 500 hectares [1]	68544 kg/day (3 shifts/day, 8hrs/shift & 6 days/week)	B/C - Process electricity from national grid; Process steam & hot water from solid residues (MF, PKS, EFB)	[8]Kyei-Baffour and Manu, 2008
				I/C - Process electricity and thermal energies from solid residues (MF, PKS, EFB) / biogas (POME) via CHP scheme	
Cassava flour	Traditional (Household scale)	2 ha farm (2 units) cultivated alternately; annual yields of 12 tons/ha [9]	192 kg/week (7 months/yr, 30 weeks/yr) [10]	B/C - Manual energies, sun-drying of chips (dry seasons of 7 months) [10]	[9]Kleih et al., 2013; [10]Dziedzoave et al, 2003
		2 ha (2 units) cultivated alternately; yields of 12 tons/ha/yr [9]; Deficit of 17.14 tons cassava from neighbouring farmers	206 kg/week (12 months (48 weeks/yr))	I/C - Manual energies, sun-drying of chips in dry seasons (7 months) , maize cobs-fired drier in wet season (5 months)	
	Semi-mechanised (Small-scale capacity of 4.8 tons cassava/day))	Purchased from neighbouring farmers	865 kg/day (6days/week (312 days/yr))	B/C - Process electricity from national grid; Cassava meal diesel fuelled drier	[11]Serpagli et al., 2010a
				I/C - Process electricity from AD/gasification of cassava peels (residue) via gas engine [11]	
	Mechanised (Industrial Scale capacity of 10 tons Cassava/day capacity) [12]	Purchased from neighbouring farmers	1800 kg/day(grating); 2400 kg/day (chipping) (2 shifts/day, 312 days/yr)	B/C - Process electricity from national grid; Cassava meal diesel fuelled drier	[12]Serpagli et al., 2010b
				I/C - Process electricity from AD/gasification of cassava peels (residue) via gas engine [11]	
Maize flour	Traditional (Household scale)	1.5 ha farm(2 units) [13] cultivated alternately; yields of 12 tons/ha/yr [14]	8.6 kg/day (180 days/yr)	B/C - Manual & sun-drying; storage of harvested cobs in traditional cribs [15]	[13]Wiredu et al, 2010; [14]MiDA, 2009; [15]De Groote, 2013
			9.82 kg/day (180 days/yr)	I/C - Manual & sun-drying; storage of shelled grains in improved metal silo [15]	
	Semi-mechanised (Small-scale capacity of 12.5 tons grains/week) [16]	Purchased from neighbouring farmers	1622 kg/day (5 days/week (10 months/yr))	B/C - Grains dried by diesel fuelled rotary grain dryer	[16]Ouaouich, 2004; [17]Belonio et al., 2012
			1622 kg/day (5 days/week (7 months/yr))	I/C - Grains dried by "maize cob-fired" dryer [17]	
	Mechanised (Industrial scale capacity of 10 tons grains/day) [18]	Purchased from Licensed Buying Companies (LBC) [19]	6464kg/day (6days/week, 10 months/yr)	B/C - Grains dried by diesel fuelled rotary grain dryer	[18]www.alibaba.com; [19]MOFA, 2014
		Purchased from neighbouring farmers		I/C - Grains dried by "maize cob-fired" dryer [17]	

NB: FFB-Fresh fruit Bunch; MF – Mesocarp fibre; PKS – Palm kernel shells; EFB- Empty fruit bunch; POME-Palm oil mill effluent; AD- Anaerobic digestion; I/C –Improved Case; B/C-Base-case

Table 3-2: Adopted parameters for mass balance calculations in the food process modelling

Crude Palm Oil (CPO) Process		Cassava Flour (CF) Process		Maize Flour (MF) Process	
Compositions	**Value (wt%)**	**Compositions**	**Value (wt%)**	**Compositions**	**Value (wt%)**
*FFB weight (kg) [1]	23	Peeled Cassava/Fresh tuber [3]	72.6	Cobs per harvested whole dehusked maize ears [7]	37
Fruit/FFB [1]	60	Peels (inedible)/Fresh tuber [3]	17.3	Hulls per grain [8]	5.3
Oil/FFB [1]	21	Peels (edible lost)/Fresh tuber [3]	11.4	Tip-Caps per grain [8]	0.8
Kernel/FFB [1]	5	Grated cassava dough/peeled cassava [3]	96.4	Germ per grain [8]	11.9
Mesocarp/fruit [1]	71	Dough lost during grating/peeled cassava [3]	1.9	Endosperm per grain [8]	81.9
Kernel/fruit [1]	21	Pressed dough/peeled cassava [3]	69.4	MC of shelled grain (wet basis) [9]	24
pks/fruit [1]	10	MC of cassava (wet basis) [4]	65	MC of dried grain for milling (wet basis) [10]	14
mf/FFB [2]	13.5	Fibre in Cassava (dry basis) [5]	2.6	MC of Tempered grain (wet basis) [11]	20
Steriliser condensate/FFB [2]	12	Initial MC of granulated wet cake (wet basis) [6]	35.2	Sorting losses (spoilt grain from field or during storage) for traditional [12], semi-mechanised [11] and mechanised respectively [11]	14; 12.5; 12.5
Clarification sludge/FFB [2]	50	Final MC of dried flour (wet basis) [6]	0.1		
Hydrocyclone wash water/FFB [2]	5				
Applicable Mass Balance Equations					
$\% \text{ CPO yield} = \frac{\text{Weight of CPO}}{\text{Weight of loose fresh fruits}} \text{ x } 100$ (Zu *et al.*, 2012)		$\% \text{ CF recovery rate} = \frac{\text{Weight of flour}}{\text{Weight of Fresh Cassava}} \text{ x } 100$ (Dziedzoave *et al.*, 2003)		$\% \text{ MF yield} = \frac{\text{Weight of flour}}{\text{Weight of clean grain after sorting}} \text{ x } 100$ (defined in this study)	

Sources: [1] FAO, 2002; [2] Yusoff, 2006; [3] Estimated from Kreamer, 1986; [4] Ukwuru and Egbonu, 2013; [5] average of reported range (1.5 – 3.7) by Monceux, 2009; [6] average of reported range by Ajiboshin *et al.*, 2011; [7] Personal estimate in Ghana, 2014; [8] May, 1987; [9] FAO, 1992; [10] FAO, 1997 and Ouaouich, 2004; [11] average reported range (5 - 20 %) by Ouaouich, 2004; [12] De Groote, 2013
*MC – Moisture content; FFB – Fresh Fruit Bunch; mf – mesocarp fibre; pks – palm kernel shell; wt% - weight percent

Furthermore, the sterilization and clarification unit operations in the CPO process under the B/C scenario were assumed to be effected with an inefficient cook stove (15% efficiency), fuelled with mesocarp fibre (mf) that contains residual oil (as additional fuel) due to the inefficient manual pressing unit operation (FAO, 2002) and supplemented with empty fruit bunches (efb). The I/C sterilization and clarification were presumed to be undertaken by means of an improved cook stove with an efficiency of 30% and fuelled with only the mf containing residual oil. The referred scheme was to ensure elimination of the efb as thermal fuel, mainly to reduce the high volumes of smoke associated with the direct combustion of efb, which poses health complications to the processors (Ugwu and Agbo, 2013).

Mechanised CPO Process

In the mechanised B/C process energy integration, it was assumed electricity was sourced from the national grid and the process thermal energies (steam and hot water) were generated from the process residues. Excess solid biomass residues are then sold as fuel to other industries or facilities. On the other hand, the I/C energy integration was based on the assumption that all the process solid biomass residues (mf, efb, and pks) are sold to an annex Combined Heat and Power (CHP) facility and all the process steam, hot water and electricity are in turn purchased from this CHP facility. Conversion of Palm Oil Mill Effluent (an organic rich liquid waste from the CPO milling process) into biogas for the mill's energy needs (in the I/C scenario) was also considered (see details in Chapter 4: FEASIBILITY ASSESSMENT OF CONVERTING PROCESS BIOMASS RESIDUES TO IN-HOUSE ENERGY IN CPO MILLS)

Cassava Flour (CF) Processing

The process modelling of CF processes were based on the work of Kreamer (1986) involving processing of cassava to 'gari', which has similar process unit operations as cassava flour (grating route) from the peeling to the pressing unit operations (see the grating cassava flour route in Figure 2-8), in conjunction with reported recovery rates of cassava flour for the various level of mechanisation by Dziedzoave *et al.*, 2003.

Traditional CF Process

Sun-drying of the cassava chips to the recommended moisture of 13 to 15% is attained in 3 days during the dry seasons (FAO, 1977). Hence the production capacity of the traditional process was reported per weekly basis. In the B/C scenario, drying of the cassava chips was assumed to be solely achieved by sun drying which is only possible for 7 months in the dry season. In the I/C scenario, the limitation of sun drying in the wet season (remaining 5 months of the year) was addressed by employing locally designed prototype wood-fired dryers in the work of FAO (1997), to increase the annual operation period to 12 months. However, the high moisture content of cassava peels residues (65 wt%) (Ukwuru and Egbonu, 2013) reduces its combustibility and limits its potential use as dryer fuel, since an external energy source is required in drying it to an appreciable moisture content. Furthermore, in order to minimize the rate of deforestation due to wood fuel dependency in rural food processing, the choice of fuel for the dryer was assumed to be maize cobs residue, as maize is often cultivated with cassava in intercropping scheme in most African settings (Adeniyan *et al.*, 2014). The annual plant throughput for the I/C was consequently increased from 24 tons fresh cassava to 41.14 tons fresh cassava with the deficit feedstock presumed to be purchased from neighbouring farmers.

Semi-mechanised and Mechanised CF Processes

In the B/C scenario, electric power was sourced from the national grid and the dryer was fuelled with diesel oil. On the other hand, the I/C scenario's electric power was generated from an anaerobic digestion (AD) or gasification of the cassava peels residue via gas-engine generator. Direct utilisation of portion of the biogas/syngas as cassava grits dryer fuel (supplementing or replacing the conventional diesel fuel) was also considered in the I/C scenario (see details in Chapter 5: FEASIBILITY ASSESSMENT OF CONVERSION OF IN-HOUSE SOLID RESIDUES FOR PROCESS ENERGY PRODUCTION IN CASSAVA FLOUR MILLS). For the mechanised CF process, the two processing routes namely grating and chipping routes (as noted for the High Quality Cassava Flour process under section 2.1.1.4) were considered.

Maize flour (MF) Processing

Traditional MF Processes

The typical 6 months maturity period of maize (MiDA, 2009) was the basis for specifying the annual production period of 6 months (remaining 6 months period in the year of harvests). In the B/C scenario, upstream storage of cobs was in traditional cribs having typical product losses of 14% due to insects and rodents' attacks while the storage mechanism of the I/C was an improved metal silo with typical product losses of 2.2% (De Groote, 2013).

Semi-mechanised MF Process

The B/C and I/C scenarios are similar except the upstream and downstream drying of the grains in the I/C are carried out by means of a "cob-fired dryer" instead of solar drying in the B/C (limited to drying season of 7 months per year). This suggestion was selected to ensure possibility of drying throughout the year, as solar drying is limited in wet seasons (FAO, 1997). It was also assumed that shelled grains are bought from licensed buying companies (LBCs) for the B/C scenario, as no cobs are required as process fuel. On the other hand, dehusked maize ears are mobilized by dedicated agents (10 personnel) from farm gate and transported for shelling and storage at the MF processing site in the I/C scenario to ensure availability of cobs for firing the dryer.

Mechanised MF Process

In the B/C approach, it was assumed shelled grains are purchased from LBCs and dried for storage at the processing facility by means of a diesel fuelled rotary grain dryer. The corresponding I/C entails employing dedicated agents (5 teams of 5 personnel each) who mobilize dehusked maize and shell at the farms by means of a mobile maize sheller. The grains are then dried at the processing facility using "maize cob-fired" dryer adopted from the work of Belonio *et al.* (2012). The required cobs for fuelling the dryer are purchased and transported alongside the grains to the processing site by the agents. The above proposed scheme for the I/C is informed by the fact that buying maize from the farm gate is cheaper than from LBC and also ensures access to the shelled cobs for fuelling the dryer (MOFA, 2014). However, maize farms are often small scale (average of 1.5 ha) and will require higher efforts in mobilizing the relatively high feedstock requirement hence the employed agents. Furthermore, transporting the whole dehusked maize ears to the processing site for shelling implies incurring extra cost and transportation of excess cobs (1446 tons) above the required amount for fuelling the dryer therefore the provision of a mobile sheller.

3.2.4 Estimation of the Energy Requirements for the Food Processes

In energy balance calculations for the food processes, only the direct energy (for instance diesel oil used by machinery) for each unit operation (process stage), but not the basic energy embodied in the unit operation (such as kinetic or potential energies in hammer mills for milling operations), were estimated and summed up (in units of MJ/kg food product). The energy balances were performed for the Base-Cases (B/C) and their corresponding Improved-Cases (I/C), except for cases where the energy forms for both the B/C and its corresponding I/C are the same such as electricity from the national grid (B/C) and electricity from the suggested renewable source (I/C). Energy forms and their lower heating values (LHV) adopted in this study are summarized in Table 3-3.

Table 3-3: Fuel Forms and their Lower Heating Values (LHV) adopted for energy balances in this study

Fuel Form	LHV (MJ/kg)
EFB (60% moisture)	5.5[1]
MF (40% moisture)	9.9[1]
Palm Kernel Shell (10% moisture)	17.1[1]
Firewood (25% moisture)	13.6[2]
CPO	37.0[3]
Diesel oil (No.2 grade)	42.8[4]
Maize Cobs	17.5[5]

Sources: [1] Panapanaan et al, 2009; [2] www.biomassenergycentre.org.uk; [3] www.corbanminerals.com; [4] www.afdc.energy.gov; [5] Sulzbacher and Rathbauer, 2014

3.2.4.1 *Biomass Thermal Energy*

Some unit operations of the traditional B/C and I/C CPO (Figure 3-2 and Figure 3-3), semi-mechanised B/C and I/C CPO (Figure 3-4 and Figure 3-5), traditional I/C CF (Figure 3-9), semi-mechanised I/C MF (Figure 3-19) and mechanised I/C MF (Figure 3-21) processes required thermal energies supplied by biomass combustion. The biomass thermal energy ($H_{Biomass}$) in the various food processes was estimated from the thermal efficiency of the cook-stove or dryers (η_{th}) as in Equation 1.

$$\eta_{th} = \frac{H_{useful}}{H_{Biomass}} \times 100 \qquad (1)$$

Where: H_{useful} - the useful portion of the biomass energy to the food process (kJ)

$H_{Biomass}$ - the thermal energy of the total solid biomass fuel input (kJ)

For the CF and MF process drying unit operations, undertaken in maize-cobs fired dryers, H_{useful} was estimated in a similar approach as the solar thermal drying energy (E_{sol}) outlined in Equations 9–12. In the CPO processes, H_{useful} was estimated as the sum of the energies required in heating the palm fruits from its initial temperature of 25°C to a final temperature of 100°C (E_{pf}), the energy required to raise the temperature of the absorbed water by the fruits from 25°C to 100°C (E_{aw}) and the energy required to evaporate the excess water at 100°C (E_{vp}). Details on evaluating the referred energies are summarised in Equations 2–4.

$$E_{vp} = M_{excess} \text{ x } \lambda_{100\,^{o}C} \tag{2}$$

$$E_{pf} = M_f \text{ x } C_f \text{ x } (T_f - T_i) \tag{3}$$

$$E_{aw} = M_{HS} \text{ x } h_f \tag{4}$$

Where: M_{excess} - mass of water vaporized (kg)

$\lambda_{100\,^{o}C}$ - enthalpy of vaporization of water at 100 °C (kJ/kg)

M_f - mass of fruit sterilized (kg)

C_f - heat capacity of the fruit (kJ/kg °C)

T_f and T_i - final and initial temperatures respectively (°C)

h_f - specific enthalpy of saturated water at 100 °C (kJ/kg)

M_{HS} - mass of absorbed water by fruit (kg)

3.2.4.2 *Diesel oil*

Diesel oil requirement in the various diesel powered units such as the digester in the semi-mechanised CPO process was estimated in the order as described in Equations 5–8.

$$DO_{hrs} = \frac{\text{Mass of daily material charge (kg)}}{\text{Equipment capacity (kg/hr)}} \tag{5}$$

$$DP_{req} = DO_{hrs} \text{ x EPR} \tag{6}$$

$$H_{diesel} = DP_{req} \text{ x } 3600 \tag{7}$$

$$V_{diesel} = \frac{H_{diesel}}{LHV_{diesel}} \tag{8}$$

Where: DO_{hrs} - the operating hours per day of the equipment

DP_{req} -the daily power requirement of the equipment (kWh)

EPR - the equipment's power rating (kW)

H_{diesel} - daily thermal energy of diesel input to equipment (kJ/day)

3600 - Conversion factor of an hour to seconds

V_{diesel} - volume of diesel input per day (m^3)

LHV_{diesel} - lower heating value of diesel (kJ/m^3)

3.2.4.3 *Solar (Thermal) Energy*

Solar (thermal) energy in the sun-drying unit operations of the food processes was estimated as the sum of energies required to raise the solids temperature from atmospheric temperatures to the final product temperatures, the energy required to heat water from room temperature to 100°C, and energies to evaporate the amount of liberated moisture as summarised in Equations 9-12.

$$E_{sol} = E_{ds} + E_{25-100} + E_{vap} \quad (9)$$

$$E_{ds} = M_{ds} \times Cp_{ds} (T_f - T_i) \quad (10)$$

$$E_{25-100} = M_{lm} \times Cp_w \times (100 - T_i) \quad (11)$$

$$E_{vap} = M_{lm} \times \lambda_{100^oC} \quad (12)$$

Where: E_{sol} - the solar (thermal) energy required in drying (J)

E_{ds} - the energy required in heating the dried solid from the initial temperature to the final product temperature (J)

E_{25-100} - the energy required to heat water from room temperature to 100 °C (J).

E_{vap} - the latent heat of vaporisation of the liberated moisture (water) (J)

M_{ds} - the mass of final dried product (kg)

M_{lm} - the mass of evaporated moisture (kg)

Cp_{ds} - the specific heat capacity of the dried solid (J/kg °C)

Cp_w - the specific heat capacity of water (4184 J/kg °C)

T_f - the final drying temperature (assumed to be atmospheric temperature of 35°C)

T_i - the initial temperature (assumed to be standard temperature of 25°C)

λ_{100^oC} - latent heat of vaporization of water at 100 °C (2.257×10^6 J/kg)

3.2.4.4 *Manual Energy*

Estimation of the manual energies was performed for only major unit operations that are totally executed by manual labour, such as the peeling and pounding unit operations of the traditional cassava flour process, and did not include manual energy utilized in monitoring or operating mechanised unit operations of the processes. The approach adopted in the estimation is from the work of Jekayinfa and Bambgoye (2006), which was based on the assumption of average human power rating of 0.075 kWh as shown in Equation 13.

$$E_m = 0.075 \times N \times t \tag{13}$$

Where: E_m - manual energy (kWh)

0.075 - average power of normal human labour (kW)

N - number of personnel involved in the process activity

t - time for accomplishing the given process activity (hrs)

3.3 Results and Discussion

Although, this chapter focused on the Base-Case (B/C) scenarios of the food processes, the developed process flow sheets (simplified) for both the Base-Case (B/C) scenarios and their corresponding Improved-Case (I/C) scenarios are presented side-by-side in Figure 3-2 to Figure 3-21 for convenience and avoidance of repetition in their subsequent comparison in Chapter 6. Likewise, a summary of the estimated mass conversion efficiencies for all the food processes considered are given in Table 3-4.

Table 3-4: Summary of estimated mass conversion efficiencies for the various food processing approaches

Parameter	Traditional		Semi-mechanised		Mechanised	
	B/C	I/C	B/C	I/C	B/C	I/C
% Crude Palm Oil yield	28.0	28.0	22	33	31.3	31.3
% Maize flour yield	84.7	84.7	77.0	77.0	76.7	76.7
% Cassava flour recovery	24.0	24.0	18.0	18.0	18.0[1];24.0[2]	18.0[1];24.0[2]

NB: All values presented are in % and estimated as defined in Table 3-2
*B/C – Base-Case; I/C – Improved-Case
[1]Grating processing route; [2]Chipping processing route

3.3.1 Energy Demands for the Base-Case Crude Palm Oil (CPO) Processes

The results of energy demands for the Base-Case CPO processes (shown in Figure 3-22) as modelled in this study suggest wide variations in process energy intensities with a minimum of 6.00 MJ/kg and maximum of 37.06 MJ/kg for the levels of mechanisation investigated. The highest and least energy intensive processes were noted to be the semi-mechanised and mechanised processes with energy intensities of 6.00 MJ/kg and 37.06 MJ/kg respectively (see Figure 3-22). Also, it can be noted from the result in Figure 3-22 that the trend of energy intensity (increase or decrease) was not consistent with the trend (increase or decrease) of mechanisation levels in the process as the semi-mechanised level's energy intensity exceeded those of the traditional and mechanised levels by 21.9 and 83.8% respectively. This could be attributed to the low CPO yield of 22% for the semi-mechanised level as compared to the 28.0 and 31.3% of the traditional and mechanised levels respectively (as shown in Table 3-4). Thus, the mass conversion efficiencies of the traditional and mechanised processes were higher than that of the semi-mechanised process.

For the traditional process, the sterilisation (boiling) and clarification (drying) operations accounted for 95.6 and 4.2% respectively of the total process energy, suggesting the sterilisation unit as the most energy intensive unit of the process (see Figure 3-2). Similarly for the semi-mechanised process, sterilisation and the clarification units accounted for 94.64 and 4.8% respectively of the process energy, which indicates the sterilisation unit is the most energy intensive unit of the process (see Figure 3-4). At the mechanised level, the steam (mainly used in the sterilisation operation), hot water (mainly utilised at the clarification unit operations) and process electricity accounted for 87.3, 8.1 and 4.6% of the total process energy respectively. Thus, the high energy intensity of the traditional (28.93 MJ/kg) and semi-mechanised (37.058 MJ/kg) B/C processes, when compared to that of the mechanised B/C process (6.00 MJ/kg) (as seen in Figure 3-22), was mainly due to the low thermal efficiency of 15% considered for the tripod stoves employed in the sterilisation and clarification unit operations in the former two processes.

Developed Process Flow Sheets for the Food Processes

Crude Palm Oil (CPO) Process Flow sheets

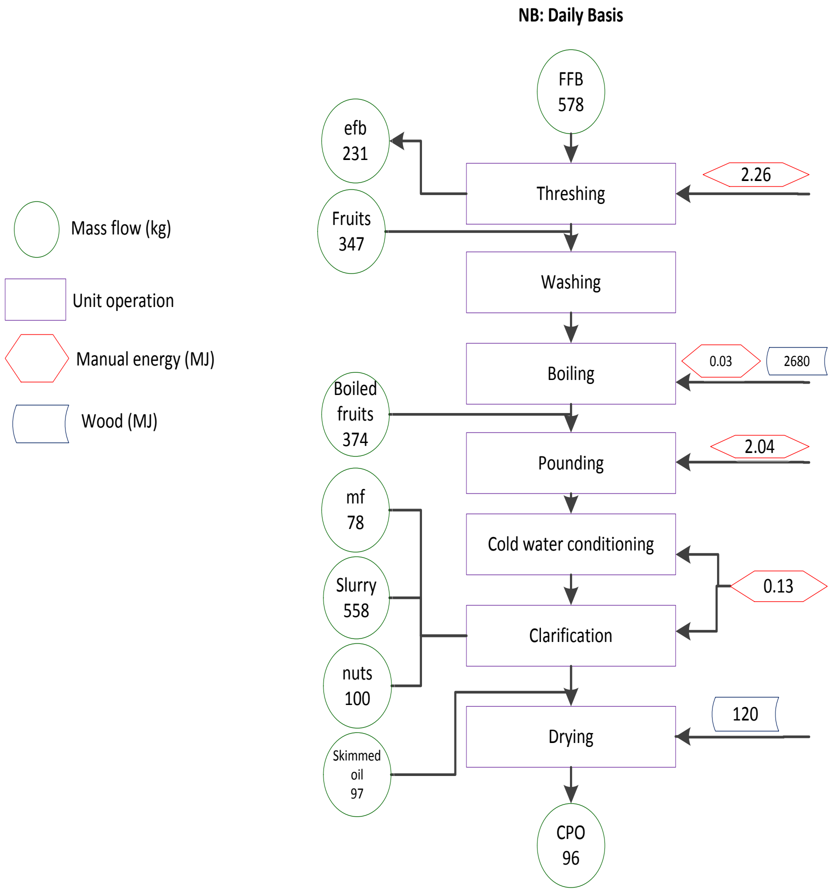


Figure 3-2: Process flowsheet of traditional crude palm oil Base-Case scenario

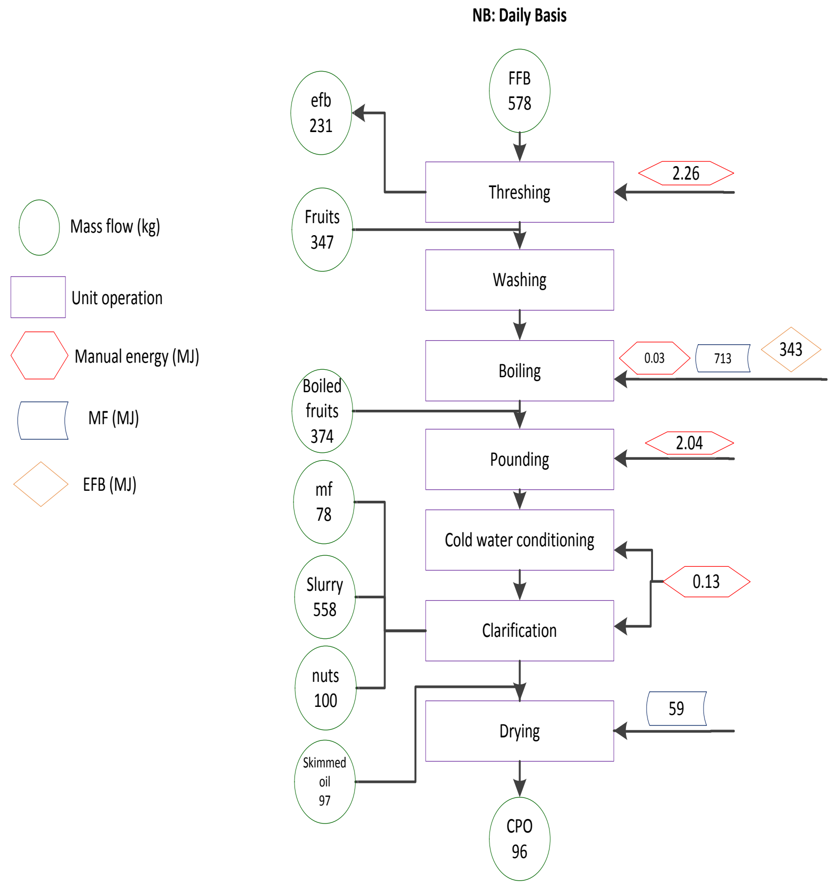


Figure 3-3: Process flowsheet of traditional crude palm oil Improved-Case scenario

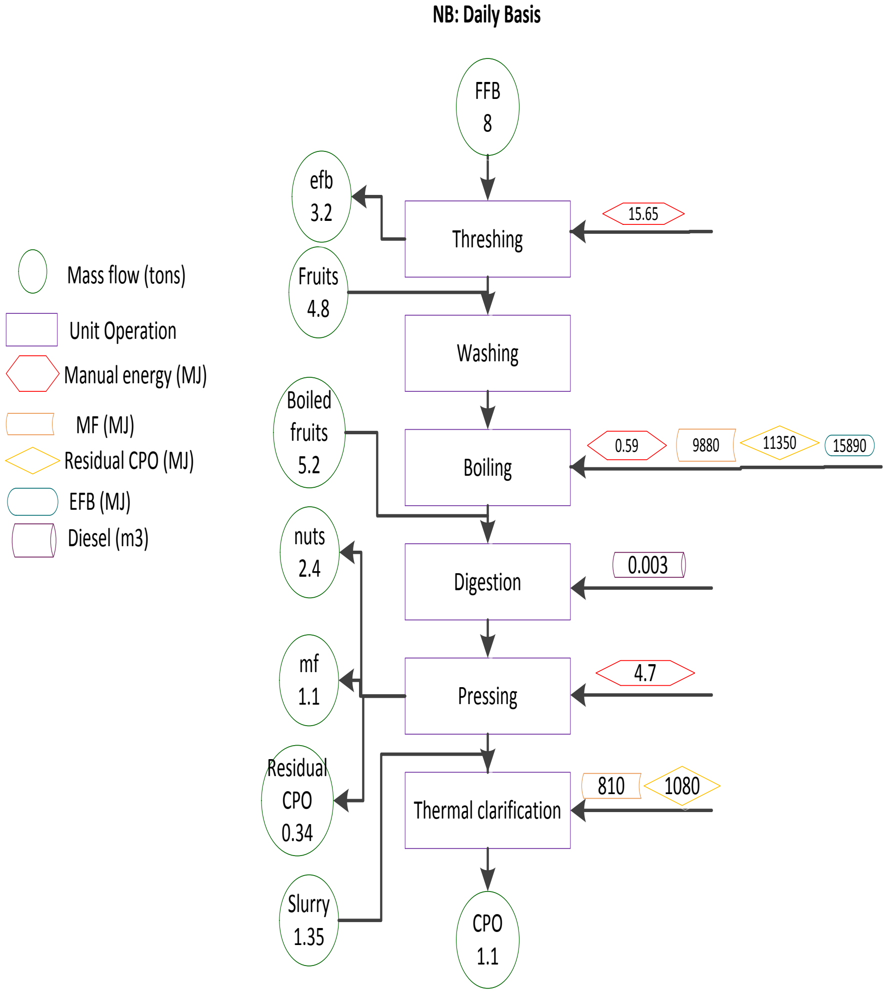


Figure 3-4: Process flowsheet of semi-mechanised crude palm oil Base-Case scenario

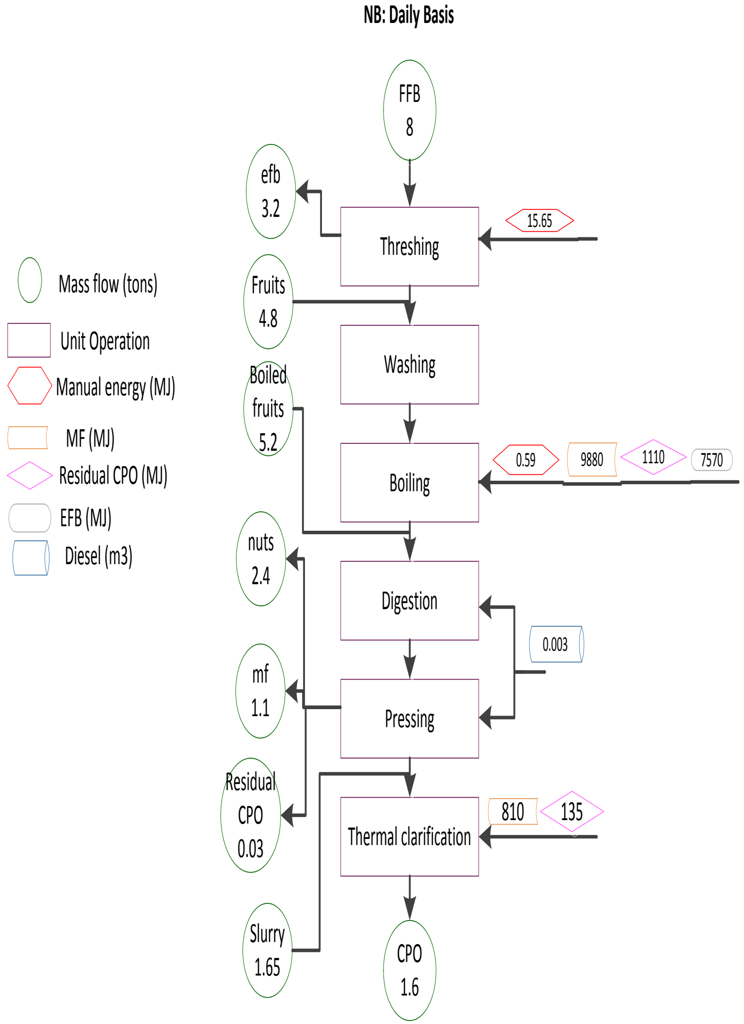


Figure 3-5: Process flowsheet of semi-mechanised crude palm oil Improved-Case scenario

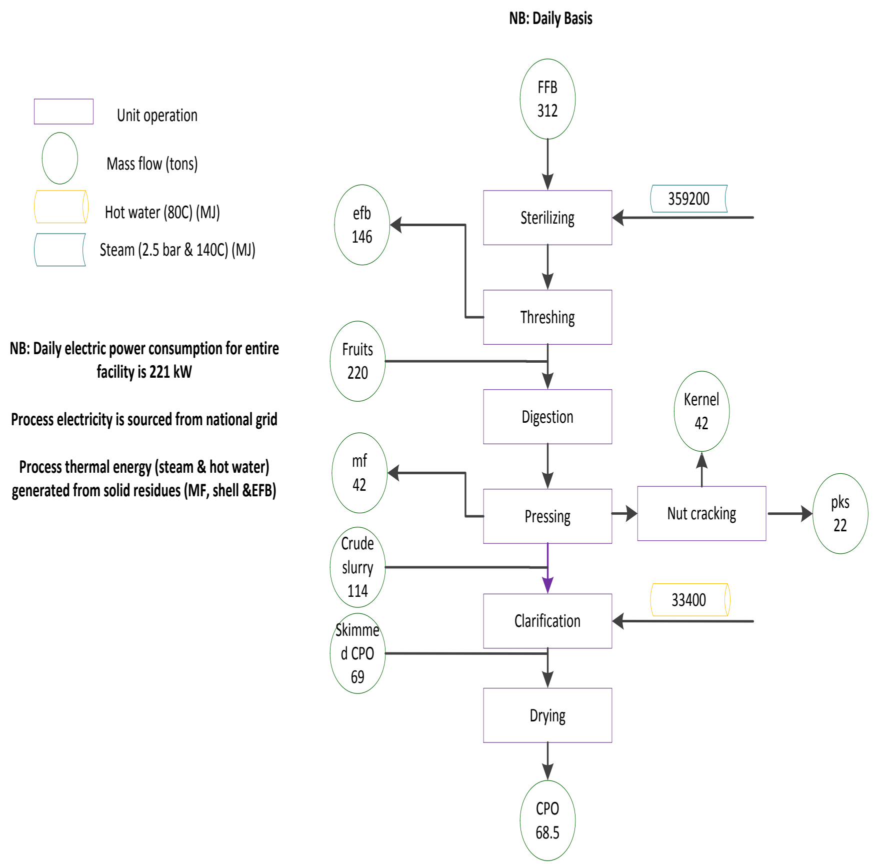


Figure 3-6: Process flowsheet of mechanised crude palm oil Base-Case scenario

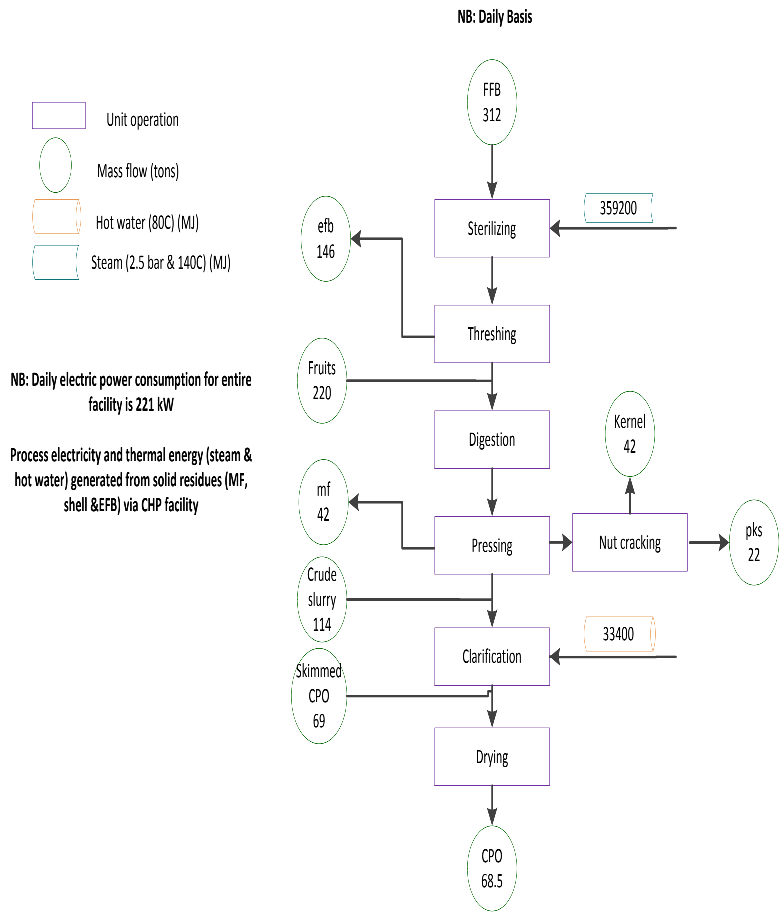


Figure 3-7: Process flowsheet of mechanised crude palm oil Improved-Case scenario

Cassava Flour (CF) Process Flow sheets

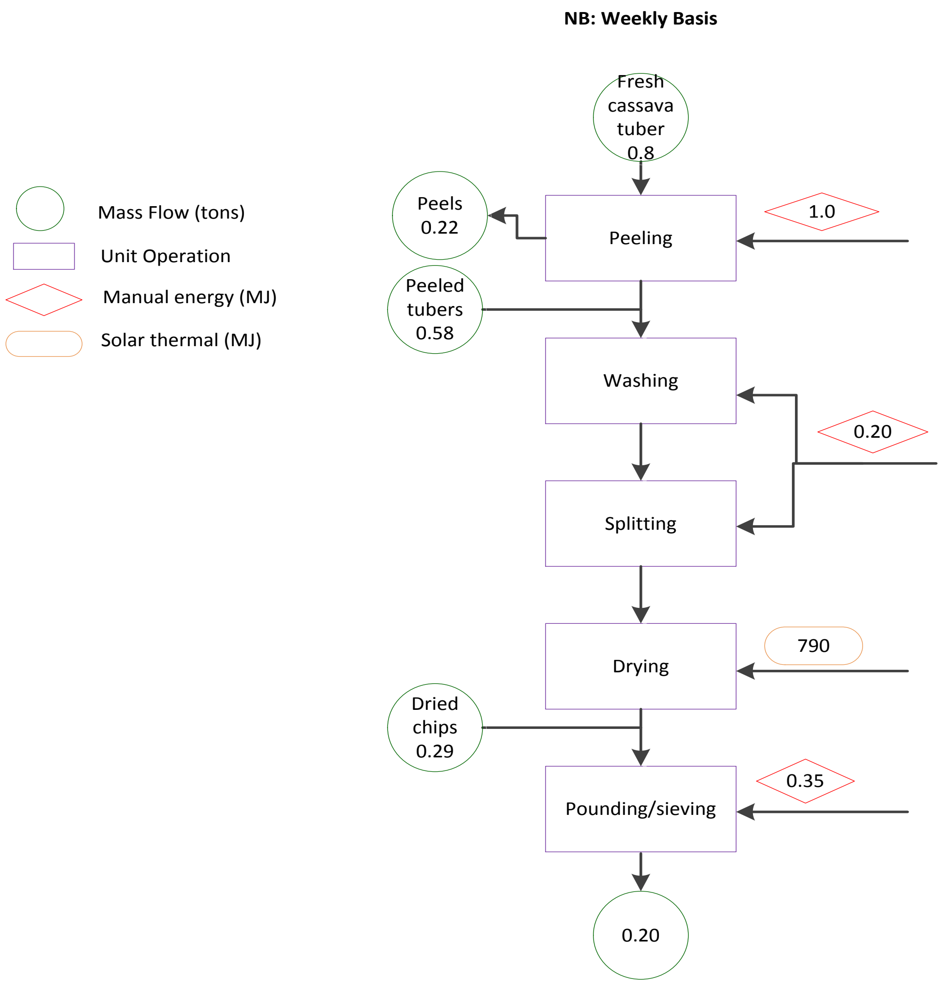


Figure 3-8: Process flowsheet of traditional cassava flour Base-Case scenario

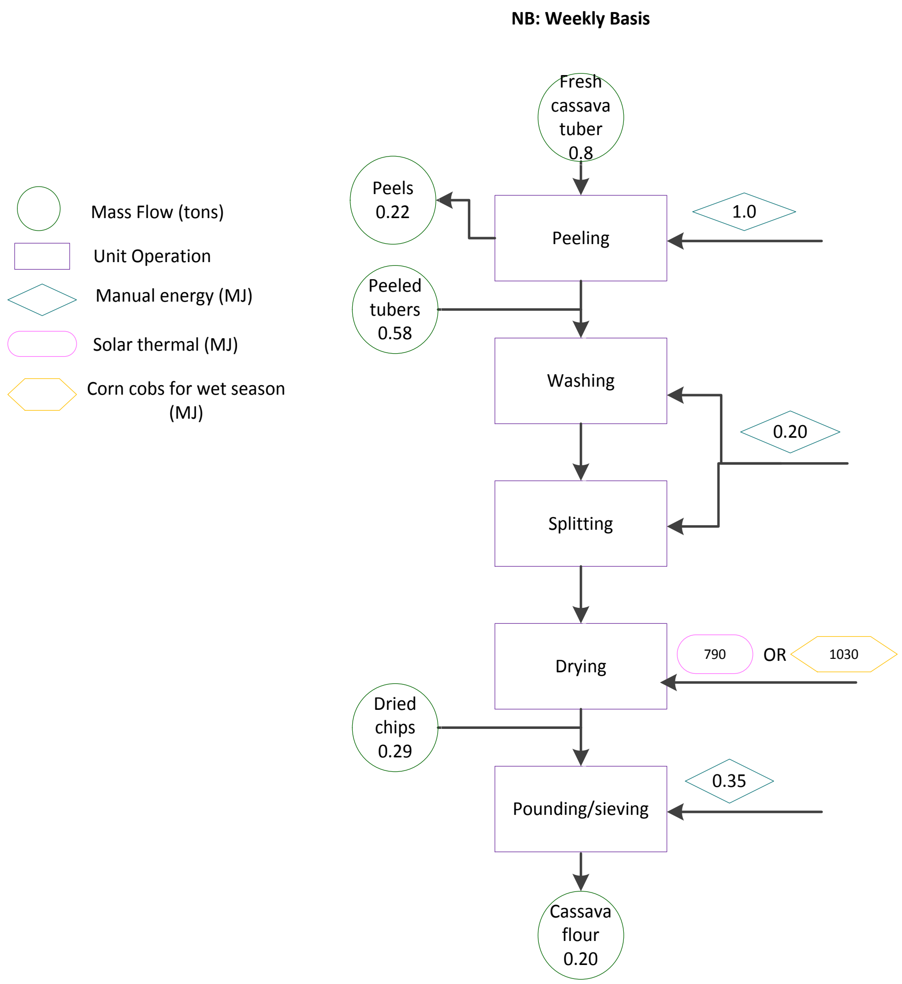


Figure 3-9: Process flowsheet of traditional Cassava Flour Improved-Case scenario

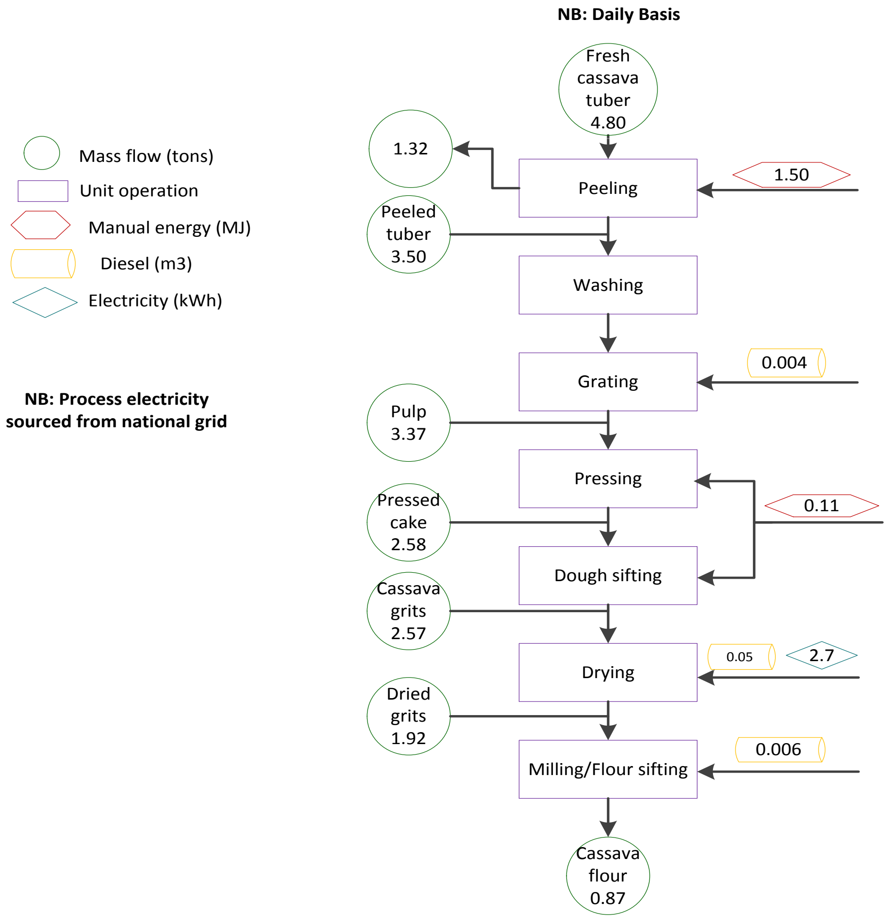


Figure 3-10: Process flowsheet of semi-mechanised cassava flour Base-Case scenario

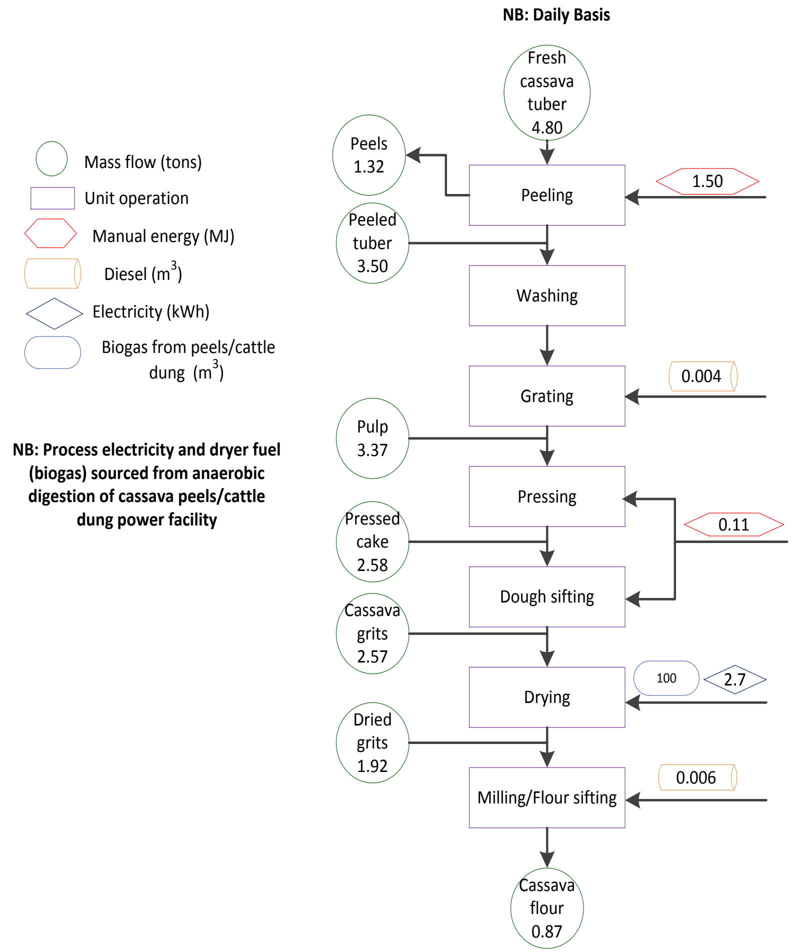


Figure 3-11: Process flowsheet of semi-mechanised cassava flour Improved-Case scenario

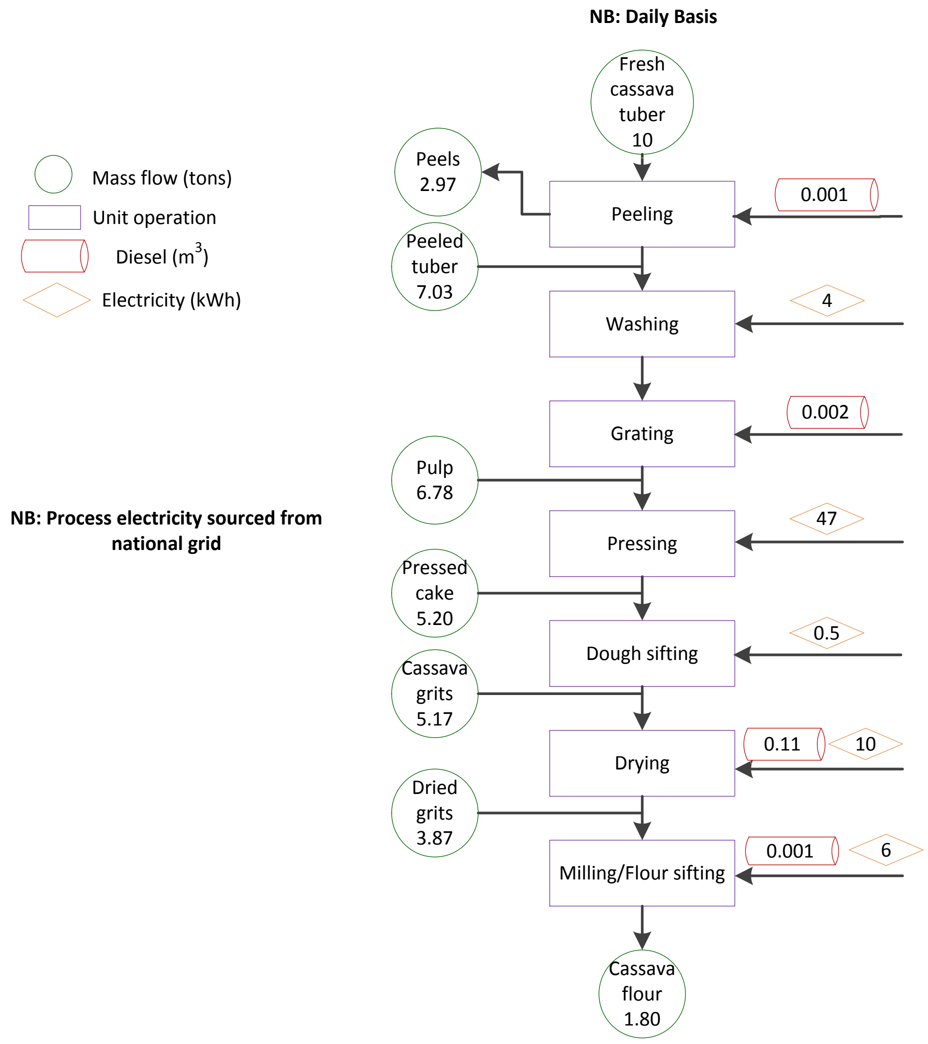


Figure 3-12: Process flowsheet of mechanised cassava flour (grating route) Base-Case scenario

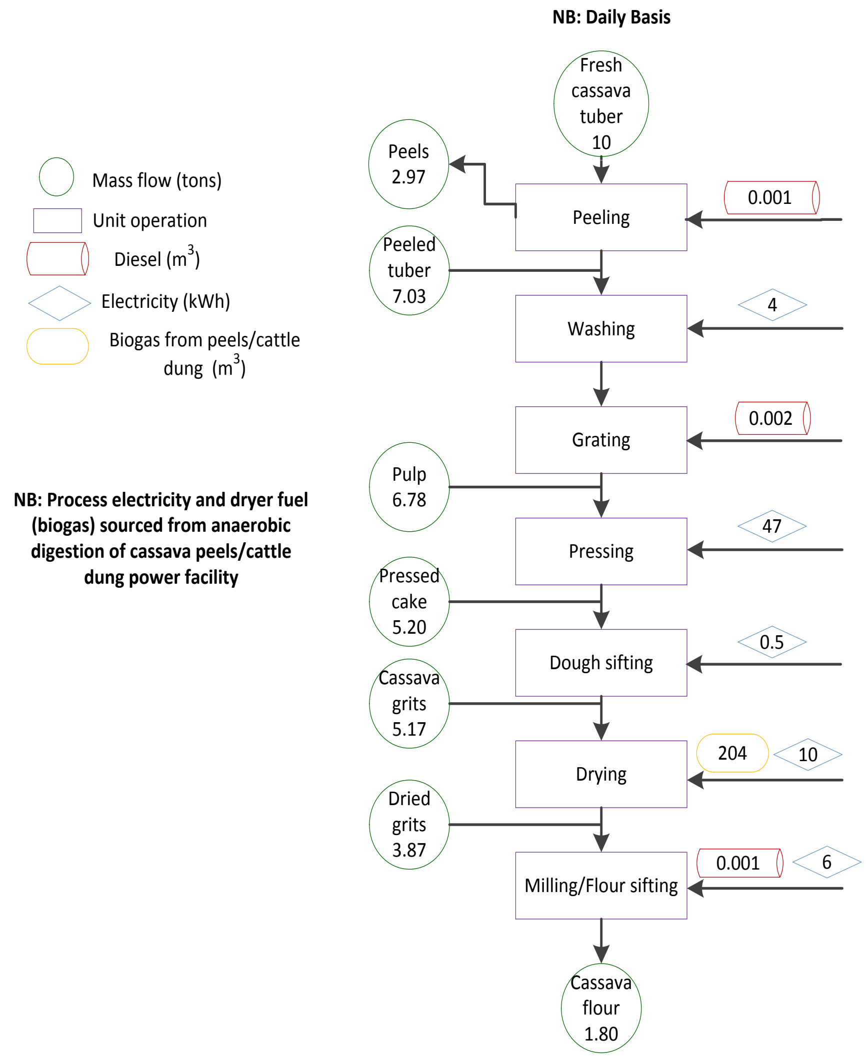
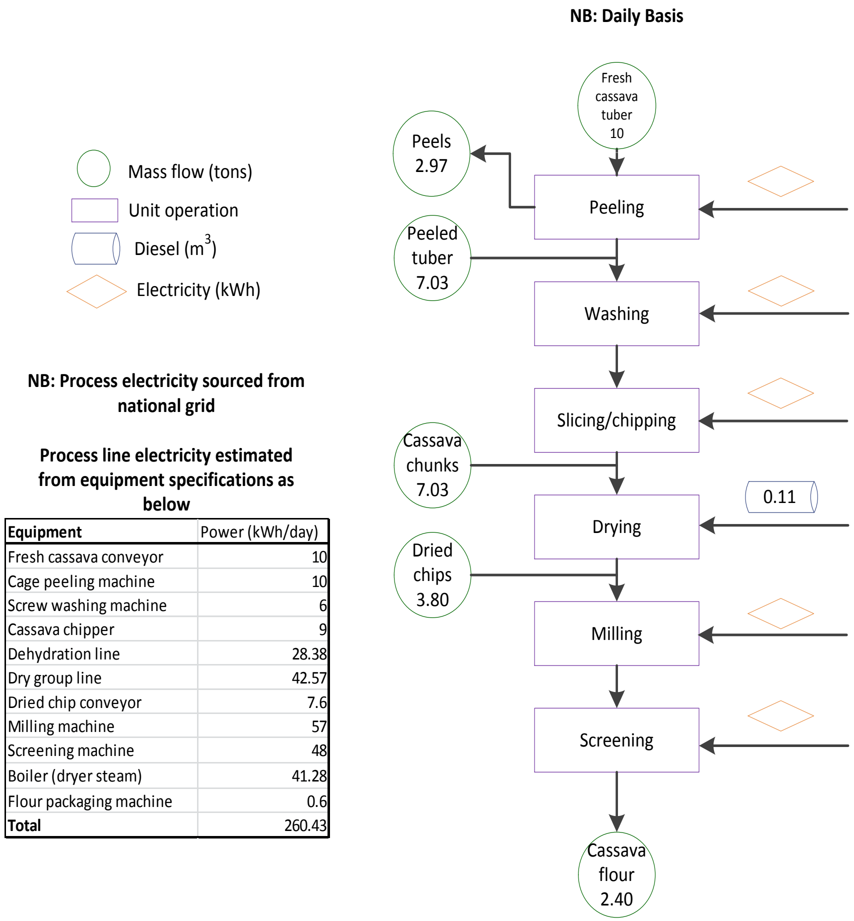
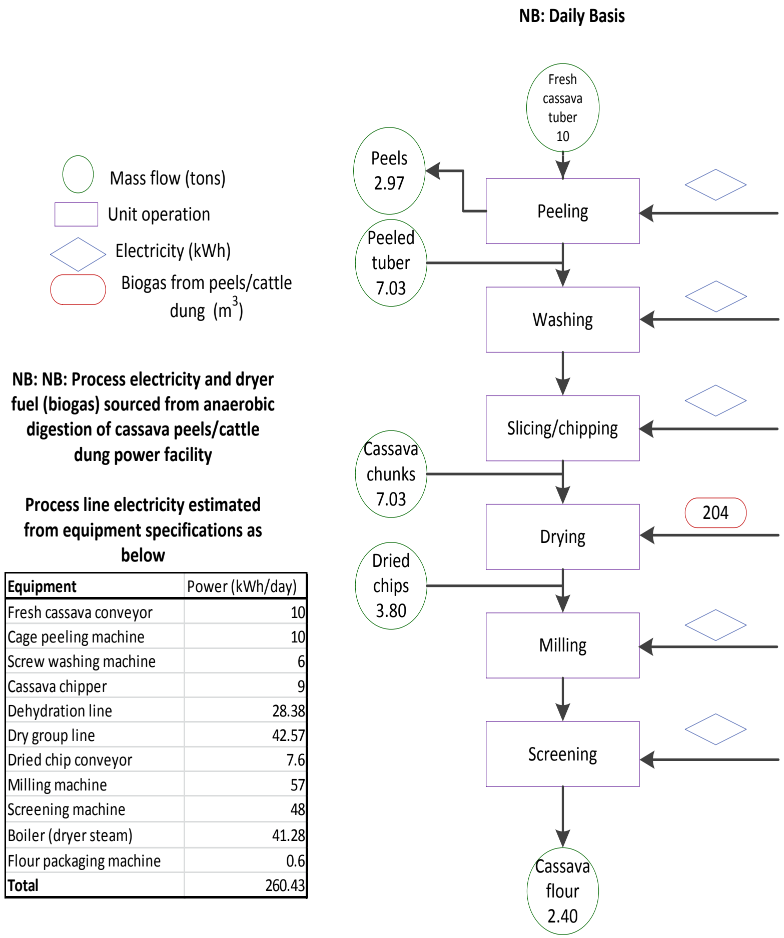


Figure 3-13: Process flowsheet of mechanised cassava flour (grating route) Improved-Case scenario



Equipment	Power (kWh/day)
Fresh cassava conveyor	10
Cage peeling machine	10
Screw washing machine	6
Cassava chipper	9
Dehydration line	28.38
Dry group line	42.57
Dried chip conveyor	7.6
Milling machine	57
Screening machine	48
Boiler (dryer steam)	41.28
Flour packaging machine	0.6
Total	260.43

Figure 3-14: Process flowsheet of mechanised cassava flour (chipping route) Base-Case scenario



Equipment	Power (kWh/day)
Fresh cassava conveyor	10
Cage peeling machine	10
Screw washing machine	6
Cassava chipper	9
Dehydration line	28.38
Dry group line	42.57
Dried chip conveyor	7.6
Milling machine	57
Screening machine	48
Boiler (dryer steam)	41.28
Flour packaging machine	0.6
Total	260.43

Figure 3-15: Process flowsheet of mechanised cassava flour (chipping route) Improved-Case scenario

Maize Flour (MF) Process Flow sheets

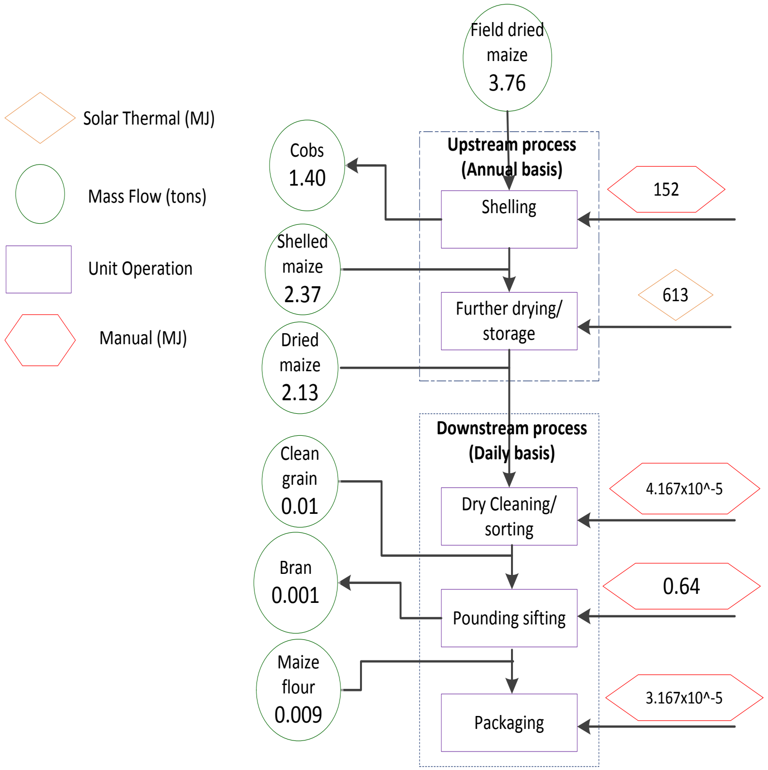


Figure 3-16: Process flowsheet of traditional maize flour Base-Case scenario

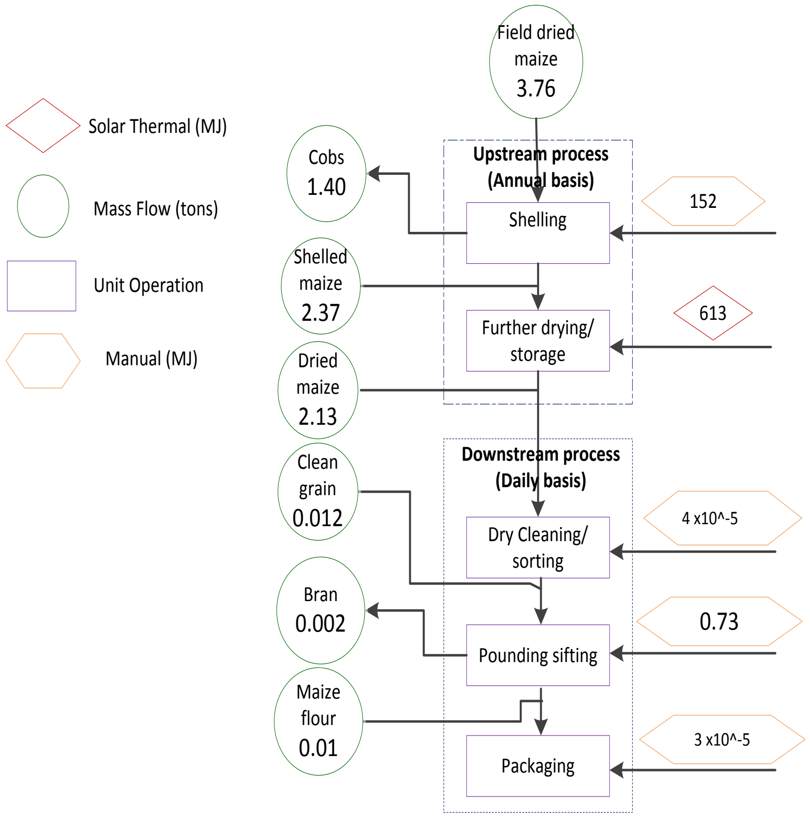


Figure 3-17: Process flowsheet of traditional maize flour Improved-Case scenario

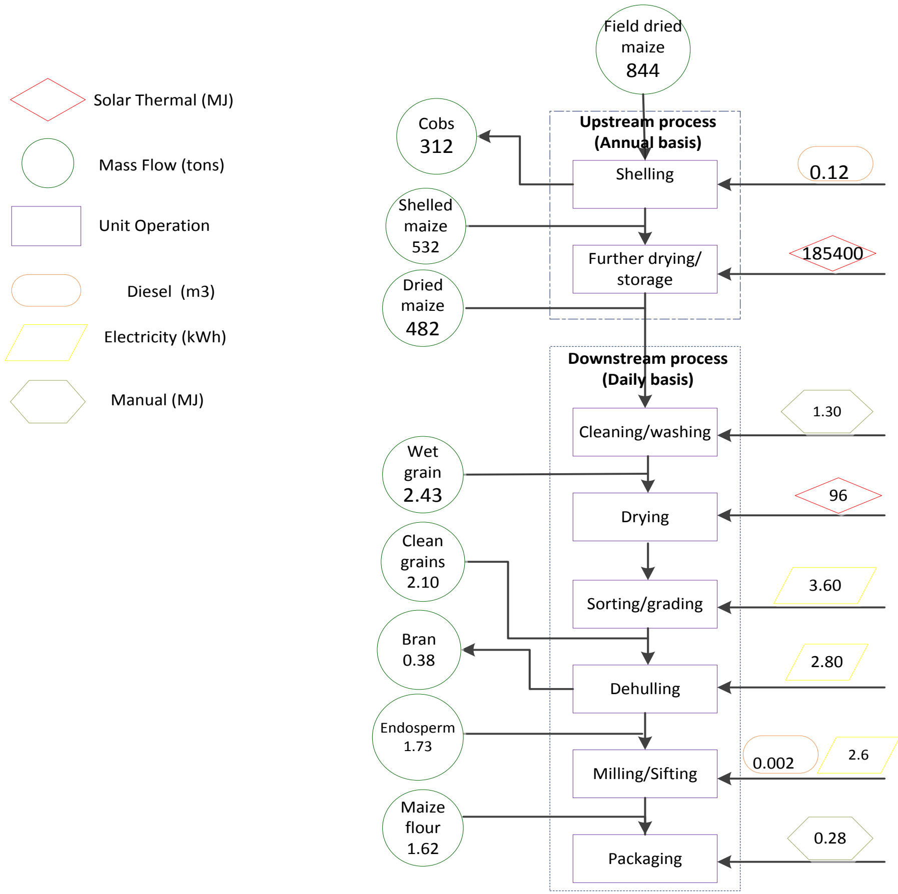


Figure 3-18: Process flowsheet of semi-mechanised maize flour Base-Case scenario

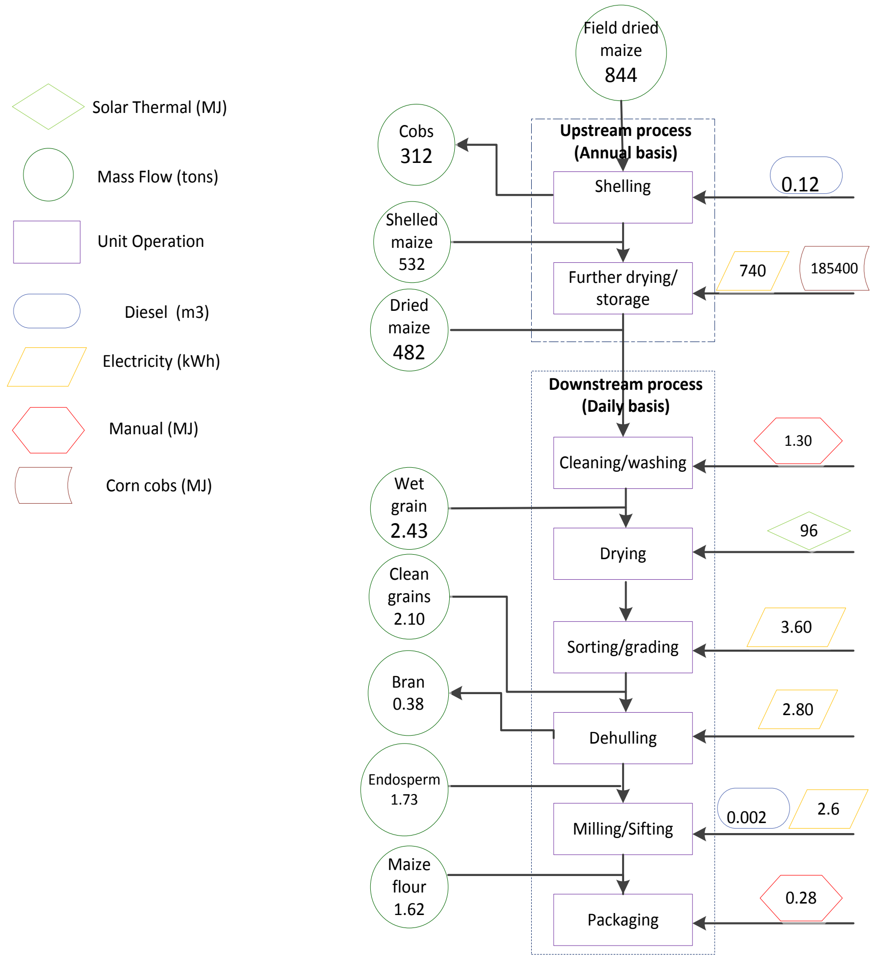


Figure 3-19: Process flowsheet of semi-mechanised maize Flour Improved-Case scenario

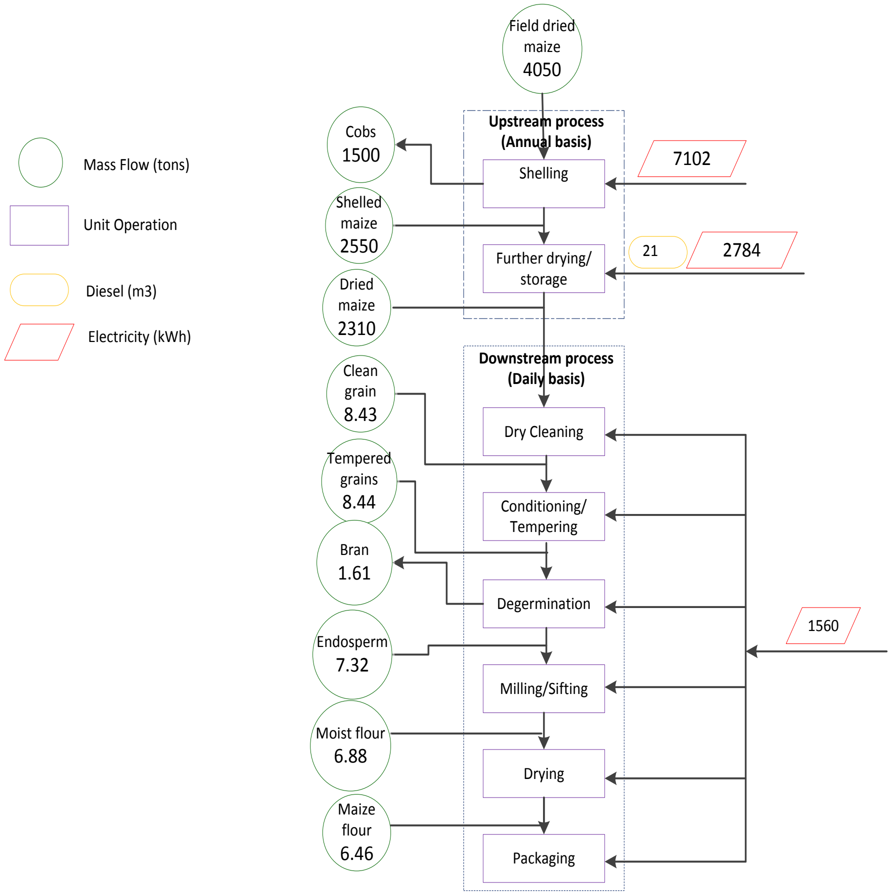


Figure 3-20: Process flowsheet of mechanised Maize flour Base-Case scenario

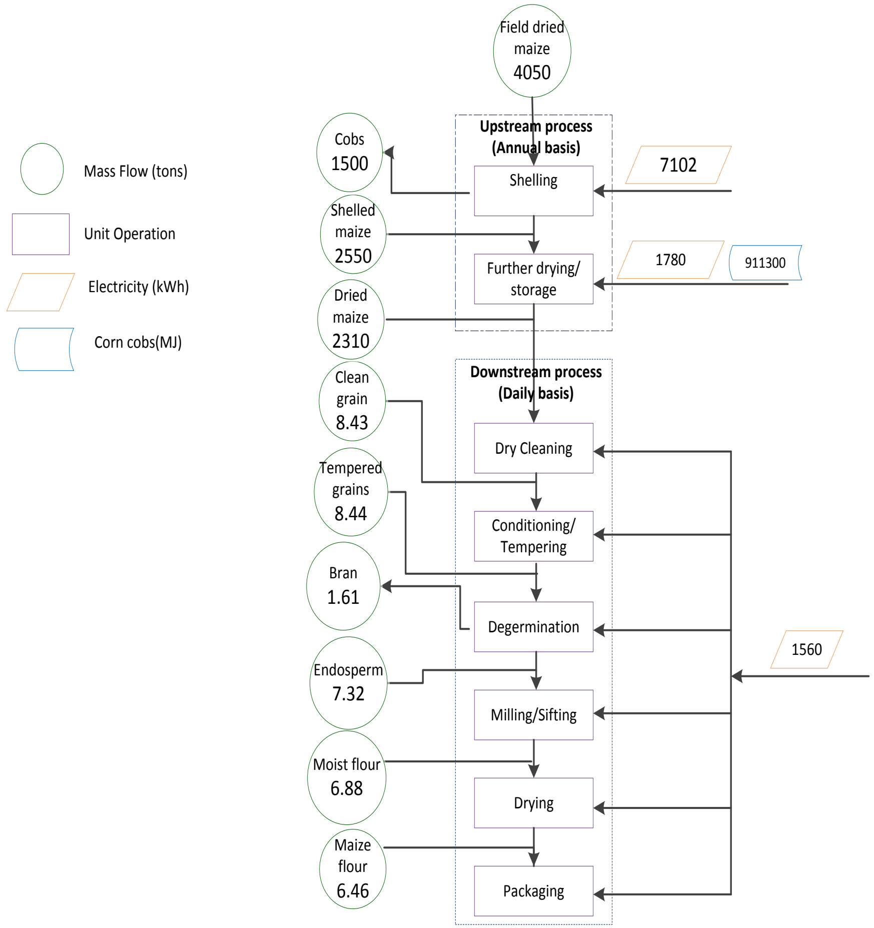


Figure 3-21: Process flowsheet of mechanised Maize Flour Improved-Case scenario

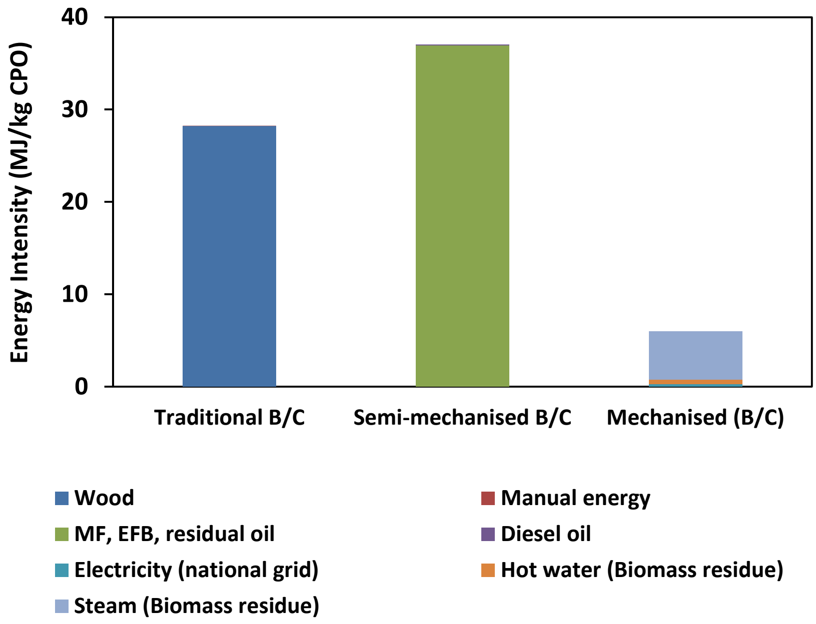


Figure 3-22: Energy demands in Base-Case crude palm oil processes

Furthermore from the result in Figure 3-22, biomass dominated all the B/C processes energy-mix with contributions of 99.8, 99.7 and 95.4% of the total process energy for the traditional, semi-mechanised and mechanised processes respectively. Also, with the exception of the traditional process, the referred biomass energies were met by the in-house efb, mf, and pks biomass residues generated at the threshing, pressing and nut-cracking unit operations of the process (see details in Figure 3-2, Figure 3-4 and Figure 3-6). The remaining process energy contributions of 0.16%, 0.05/0.24%, and 4.6% were from manual, manual/diesel oil, and electricity for the traditional, semi-mechanised and mechanised processes respectively (see details in Figure 3-2, Figure 3-4 and Figure 3-6). Hence, the only non-renewable energy contribution was from diesel at 0.24% of the energy demands in the semi-mechanised level which was completely consumed by the digestion unit (see Figure 3-4). This suggests minimal room for integration of renewable energy into the CPO processes as modelled in this study.

3.3.2 Energy Demands for the Base-Case Cassava Flour (CF) Processes

The energy demands for the B/C cassava flour processes are summarised in Figure 3-23, and suggested a consistent trend of decreases in the process energy intensity as the level of mechanisation was increased. In addition, the energy intensities ranged between 1.96-4.13 MJ/kg, with the mechanised option (chipping route) being the least energy intensive process (see Figure 3-23). The noted trend could be attributed to combining effects of differences in the mass and energy efficiencies, and the energy forms in the processing approaches (Akinoso *et al*. 2013). Also, from the energy mix and contributions in the B/C CF processes (shown in Figure 3-23), a trend of increasing electricity demand with an increase in level of mechanisation of the process can be noted. From the process energy demand result (in Figure 3-23), electricity contributed 0.44, 5 and 20% of the energy mix in the semi-mechanised, mechanised (grating) and mechanised (chipping) processes respectively. Furthermore, for the two mechanised process levels investigated (i.e. grating and chipping routes), the principal process energies were diesel and electricity with the former dominating the energy-mix contributions in both referred processes (Figure 3-23).

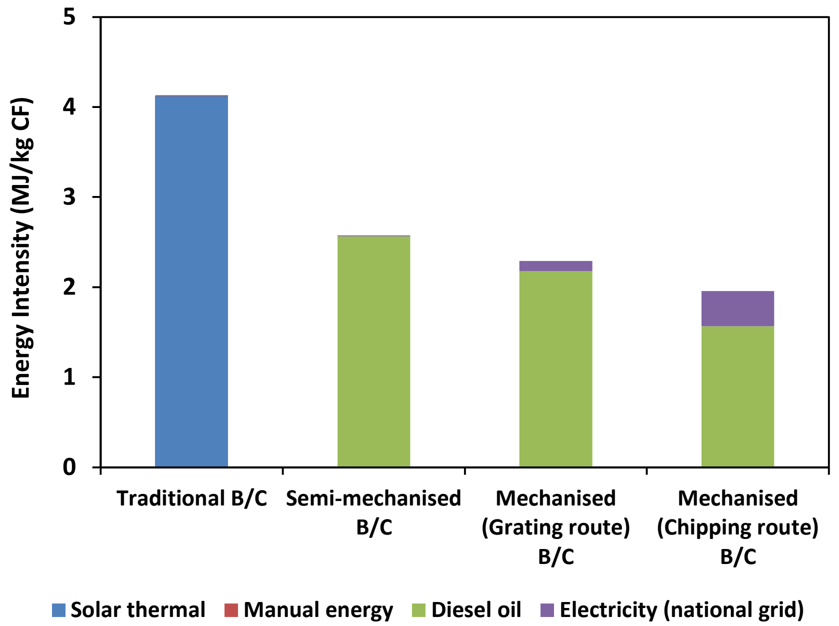


Figure 3-23: Energy demands in the Base-Case scenarios of cassava flour processes

In addition, from Figure 3-23 it can be noted that diesel dominated the energy-mix streams of the semi-mechanised, mechanised-grating and mechanised-chipping B/C processes with contributions of 99.5, 95 and 80.4% of the total process energy respectively. Additionally, of the total diesel consumption in the referred processes, the highest demand was by the drying units which consumed 84.2, 96 and 100% of the total diesel requirement by the process respectively (see details in the process flow sheets in Figure 3-10, Figure 3-12 and Figure 3-14). At the traditional level, solar thermal energy as drying energy in the process (see Figure 3-8) dominated the process energy-mix with 99.8% and the remaining 0.19% of the total energy was from manual labour (as shown in Figure 3-23). Thus, aside being the most energy intensive unit operation of the process, the drying unit operation of the CF process also created the largest opportunities for renewable energy integration in the semi-mechanised and mechanised CF processes. In instances where the national grid electricity is generated from fossil fuel based thermal power plants, as is the case in Ghana with 47.9% of the national grid electricity generation from fossil fuelled thermal power plants (VRA, 2014), electricity generation from a renewable energy source becomes the second important avenue for renewable energy integration in the CF process.

3.3.3 Energy Demands of the Base-Case Maize Flour Processes

Figure 3-24 shows the results of the energy demands of the modelled B/C maize flour processes. The results show a consistent trend of decreasing process energy demands as the level of mechanisation increases. Furthermore, variations in the energy demands of the processes ranging between 0.17 and 1.36 MJ/kg was noted (Figure 3-24). From the energy demands of the traditional level given in Figure 3-24, manual energy dominated the energy-mix with a contribution of 99.99% and solar thermal at 0.001%. This finding is in agreement with literature's suggestion of the traditional MF processing being manual energy intensive (FAO, 1997). On the other hand, solar thermal energy (as drying energy) contributed 89.2% of the energy demands for the semi-mechanised process with diesel, manual, and electricity accounting for the remaining 7.8%, 2.8% and 0.2% respectively of the total process energy (Figure 3-24). Also from the result (Figure 3-24), electricity was the principal energy source at the mechanised level with a contribution of 64.3% of the total process energy and the remaining 35.7% supplied by diesel with the latter entirely consumed by the drying unit (see details in Figure 3-20). Also, considering the entire mechanised MF B/C process had 8 process units (see Figure 3-20), the consumption of 35.7% of the total process energy by the drying unit suggests the drying unit is the most energy intensive unit operation of the mechanised process.

On the other hand, solar thermal energy was the principal energy form in the semi-mechanised level's energy-mix at 89.2% followed by diesel at 7.8% of the total process energy demand (see Figure 3-24). The milling and shelling unit operations accounted for 76.3 and 23.7% consumption of the referred total diesel demand in the semi-mechanised process (see details in Figure 3-18). Thus, the opportunity for renewable energy integration in the B/C MF processes as modelled are at the drying unit operation for the mechanised level, and the milling/shelling unit operations for the semi-mechanised level.

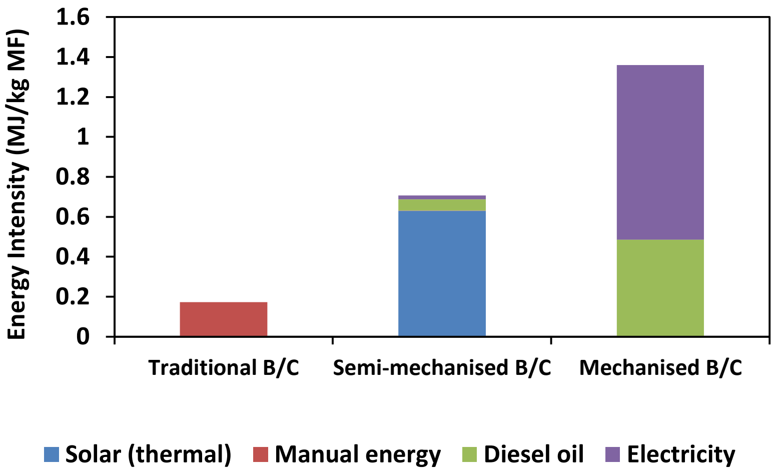


Figure 3-24: Energy demands in the Base-Case scenarios of maize flour processes

The drying unit operation consumed 69.6, 89.2 and 36.1% of the traditional, semi-mechanised and mechanised MF process energies respectively (see Figure 3-16, Figure 3-18 and Figure 3-20). The milling unit operation accounted for 30.4, 6.0 and 3.1% of the traditional, semi-mechanised and mechanised MF process energies respectively (see Figure 3-16, Figure 3-18 and Figure 3-20). Hence, the drying unit operation was the most energy intensive unit, followed by the milling unit operation in the MF processes. A related study on energy demands for two commercial cowpea flour production facilities revealed the energy intensities were 3.8 and 63.07 MJ/kg for facilities A and B respectively (Akinoso *et al*. 2013). The drying and milling units were also identified as the most energy intensive units for facilities A and B and expended 51% and 63% of their referred total process energies (Akinoso *et al*. 2013). Therefore, the noted trend of drying and milling as the most energy intensive process units in the MF processes corroborates with the referred findings of Akinoso *et al*. (2013). The differences in the estimated energy intensities for the cowpea flour and maize flour processes could be associated with the difference in feedstock (cowpea or maize) physiology and process energy sources considered. The result (Figure 3-24) further showed a trend of increasing energy intensity with increase in the level of mechanisation in the MF process. This could be due to differences in the energy forms, energy and mass conversion efficiencies of the process equipment (Akinoso *et al*. 2013). In addition, electricity demand in the MF process (as modelled in the study) decreases with decrease in the level of mechanisation and accounted for 64.3%, 2.8% and nil of the total process energy in the mechanised, semi-mechanised and traditional B/C process energy demands respectively (as shown in Figure 3-24).

3.3.4 Biomass Residues Potential and In-house Uses in the Food Processes

Table 3-5 highlights the rate of generation of biomass residues (MJ/kg food product produced) and the extent of its utilisation for in-house energy purposes (MJ/kg food product produced) in the modelled Base-Case (B/C) food processes. The biomass residue assessment (presented in Table 3-5) revealed for the food processes under study (CPO, CF and MF processes), high biomass residue generation potential exist at all the levels of mechanisation investigated.

In the CPO process, the rate of generation of mesocarp-fibre (mf) and empty fruit bunch (efb) residues (which was common to all the mechanisation levels) ranged between 6.09-10.13 and 11.72-16.67 MJ/kg respectively (see Table 3-5). Nuts (kernel and palm kernel shells (pks)) residues were specific to the traditional and semi-mechanised processes while kernels and pks (obtained after cracking the nuts) were generated in only the mechanised process (see Figure 3-2, Figure 3-4 and Figure 3-6). The rates of generation of the nuts, kernels and pks residues in the referred processes were noted to be 17.90-39.11, 10.53 and 5.47 MJ/kg CPO respectively (shown in Table 3-5). However, only few portions of the generated residues were utilised as the CPO process energy sources in the semi-mechanised and mechanised levels, while utilising residues as process energy was completely non-existent in the traditional level (see Table 3-5). As shown in Table 3-5, out of the referred generated residues for the semi-mechanised process, only 100% mf and 90.3% efb are utilised as heating fuel for the boiling and clarification unit operations of the process (see Figure 3-4). At the mechanised level, only 56.4, 12.3 and 50.6% of the generated mf, efb and pks residues (respectively) were utilised for process steam and hot water generation (see Table 3-5). Considering external wood fuel, as heating fuel for the boiling and clarification unit operations (see Figure 3-2 and Figure 3-22), supplied 99.5% of the total process energy (corresponding to 28.78 MJ/kg CPO) in the B/C traditional CPO process (see Figure 3-22), the total biomass residues (nuts, mf and efb) energy of 38.98 MJ/kg (see Table 3-5) could be enough for the heating purposes. However, the kernels in the nuts are more valuable as kernel oil feed, thus the nuts are often sold for kernel oil extraction (Adjei-Nsiah *et al.*, 2012). This implies that the available mf and efb residues with total energy of 21.08 MJ/kg (see Table 3-5) can only be adequate for the process heating energy demands if the low thermal efficiency of the tripod stove (15%) is improved.

Also, the low energy demand of 6 MJ/kg CPO for the mechanised CPO process (see Figure 3-22), as compared to the estimated total energy of 23.28 MJ/kg CPO for the available mf, efb and pks solid residues (see Table 3-5), suggests the referred residues could suffice for the total in-house energy demand. Husain *et al*. (2003) noted the total process energy (steam, hot water and electricity) demands of a mechanised CPO facility (often termed CPO mill) could be met by the solid residues (mf, efb and pks) by means of established technologies such as biomass-fuelled boiler and steam turbine technologies. Thus, the generated solid residues (mf, efb and pks) in the mechanised CPO process could be strategically utilised to meet all the process thermal energy (steam and hot water) and electricity rather than utilising only portions of the residues for process thermal energy generation. Similarly, the estimated POME energy content (estimated as its potential biogas energy content) of 44.25 MJ/kg CPO (see Table 3-5) could also be sufficient for the in-house energy, if the energy requirement for its anaerobic digestion to biogas and the conversion of the biogas to the in-house energy processes are within the limits of the excess 38.25 MJ/kg CPO energy from the POME.

In the cassava flour (CF) processes, cassava peels (inedible and edible portions of tuber lost to peels during peeling) were the common biomass residues generated in all the mechanisation levels considered (see Figure 3-8, Figure 3-10, Figure 3-12 and Figure 3-14). It was further noted that the rate of generation of the peels ranged between 5.32-7.69 MJ/kg CF for the levels of mechanisation considered (shown in Table 3-5). The high energy contents of the generated peels (5.32-7.69 MJ/kg CF) when compared to the estimated total CF process energies of 1.96-4.13 MJ/kg CF (see Figure 3-23) suggests the potential of utilising the peels as in-house energy resources.

However, the peels are not utilised for in-house energy purposes in the B/C CF processes (see Table 3-5). This could be due to the high moisture content of the peels (65 wt% wet basis) (Ukwuru and Egbonu, 2013), which makes it less suitable for direct in-house energy applications in the CF processes, such as direct combustion for drying purposes. According to Serpagli *et al*. (2010a), cassava peels could be converted into combustible gases (syngas or biogas), which could be utilised for generating electricity via gas engine generators or fuelling dryers. This could be interesting, particularly for the case of the semi-mechanised and mechanised CF processes, as their energy forms namely electricity and diesel for dryer fuelling (see Figure 3-10, Figure 3-12 and Figure 3-14) are similar to the referred end-use energy forms.

Table 3-5: Rate of generation and in-house energy application of biomass residues in the food processes

Food Process	Mechanisation level	Rate of generation and in-house applications of process biomass residues			
		Residue form	Amount generated (MJ/kg product)	Amount used for in-house energy purposes (MJ/kg product)	Amount remaining* (MJ/kg product)
Crude Palm Oil	**Traditional**	Nuts (pks/kernel)	17.90	0	17.90 (100)
		mf	7.97	0	7.97 (100)
		efb	13.11	0	13.11 (100)
	Semi-mechanised	Nuts (pks/kernel)	39.61	0	39.61 (100)
		mf	10.13	10.13	0 (0)
		efb	16.67	15.05	1.62 (9.7)
	Mechanised	mf	6.10	3.44	2.66 (43.6)
		efb	11.72	1.44	10.28 (87.7)
		pks	5.47	2.77	2.70 (49.4)
		kernels	10.53	0	10.53 (100)
		POME	44.25	0	44.25 (100)
Cassava Flour	**Traditional**	Peels	5.32	0	5.32 (100)
	Semi-mechanised	Peels	7.09	0	7.09 (100)
	Mechanised (grating)	Peels	7.69	0	7.69 (100)
	Mechanised (chipping)	Peels	5.77	0	5.77 (100)
Maize Flour	**Traditional**	Bran	0.32	0	0.32 (100)
		Cobs	15.72	0	15.72 (100)
	Semi-mechanised	Bran	1.19	0	1.19 (100)
		Cobs#	16.87	0	16.87 (100)
	Mechanised	Bran	1.27	0	1.27 (100)
		Cobs#	16.94	0	16.94 (100)

mf – mesocarp fibre; efb – empty fruit bunch; pks – palm kernel shell; POME – palm oil mill effluent
* Values in parenthesis represent percentage of generated amount
# The cobs are technically not generated residues in the Base-Case (B/C) semi-mechanised and mechanised MF processes as their assumed feedstock was shelled grains. However, the given cob residues estimates is to provide the cobs potential should whole field dried maize cob be employed as feedstocks.
NB: Energy contents of the residues were estimated based on their Lower Heating Values (LHV). LHVs for mf,efb, pks and maize cobs used are given in Table 3-3; maize bran - 5.09 MJ/kg (Junior *et al.*, 2014); cassava peels - 4.66 MJ/kg (Sen and Annachhatre, 2015); nuts - 17.26 MJ/kg (estimated from the mass fractional composition of the nut - kernel cake - 0.663, kernel oil - 0.014 and pks - 0.323 (FAO, 2002; Jekayinfa and Bamgboye, 2008) and the LHVs of kernel cake - 16.87 MJ/kg (Kolade et al., 2006), kernel oil - 39.70 MJ/kg (Jekayinfa and Bamgboye, 2008) and pks - 17.10 MJ/kg (Panapanaan et al., 2009)); kernel - 17.35 MJ/kg (estimated similarly as for the nut, using mass fractional composition of kernel - kernel cake - 0.979 and kernel oil - 0.021 (Jekayinfa and Bamgboye, 2008) and their given LHVs); POME energy content was assumed to be equivalent to the energy content of potential biogas yield from the POME, thus its LHV (16.68 MJ/kg POME) was estimated from average biogas yield of 0.695 m^3/kg POME and LHV of biogas at 24 MJ/m^3 (Yeoh, 2004).

In the B/C scenarios for the maize flour (MF) processes, bran (hulls, tip-caps and germ components of the maize) was noted to be the common biomass residues generated in the downstream unit operations of the processes, while cobs were generated in only the traditional process (see Figure 3-16, Figure 3-18 and Figure 3-20). This was due to the feedstock for the semi-mechanised and mechanised B/C processes being shelled grains purchased from licensed buying companies (LBCs), while the feedstock for the traditional processes was whole unshelled cobs (see section 3.2.3.1: General Assumptions). Hence the upstream processes (shelling and drying), as modelled in this study, are outside the boundaries of the B/C MF processes (see Figure 3-16, Figure 3-18 and Figure 3-20). Though the cobs are not utilised as process energy resources in the B/C MF processes (as shown in Table 3-5), demonstrations showed it was technically feasible to utilise the cobs as fuels for biomass-fired maize dryers (Belonio *et al.*, 2012). Furthermore, the high rate of generation of the cobs- 15.72-16.94 MJ/kg MF (seeTable 3-5), when compared to the estimated drying energy intensities of the semi-mechanised- 0.63MJ/kg MF and mechanised- 0.48 MJ/kg MF processes (see Figure 3-24), suggests the high potential of the cobs sufficing in the drying energy demands of the MF processes. Thus, it might be worthy to consider purchasing and transporting the cobs to the MF processing site or adopting the whole unshelled cobs as feedstock for feasible integration of the cobs as energy resources in the semi-mechanised and mechanised MF processes. On the other hand, the bran residues are noted to be rich in nutrients such as protein and oils and therefore often sold for animal feed production (Ouaouich, 2004), hence not likely to be used for in-house energy purposes.

3.4 Conclusions

The B/C CPO production process models revealed the process energy intensities ranged between 6.00–37.06 MJ/kg. The sterilisation unit operation was the most energy intensive unit operation in the CPO processes and accounted for 95.6, 94.6 and 87.6% of the traditional, semi-mechanised and mechanised processes' energy demands respectively. This was mainly due to low thermal efficiencies of tripod stoves of 15% (REN21, 2010) used in the sterilisation operations for the traditional and semi-mechanised processes, and the thermal efficiency of 75% of the steam boiler (US EPA, 2008) employed in the mechanised process. Thus, efforts in improving the energy performances of the traditional and semi-mechanised CPO processes should be centred on improving the tripod stoves thermal efficiencies, which could be achieved with existing improved cook stoves that have higher thermal efficiencies (Energica, 2009).

The estimated energy intensities for the CF production processes ranged between 1.96–4.13 MJ/kg. These estimates were higher than 0.32 MJ/kg reported for a CF production facility (Jekayinfa and Olajide, 2007). The noted differences in energy intensities could be attributed to variations in the energy sources and processing approaches. Also, the drying units were noted to be the most energy intensive units which expended 99.8, 84.2, 92.1 and 82.2% of the total process energy for the traditional, semi-mechanised, mechanised-grating and mechanised- chipping CF processes respectively. This could be attributed to the high energy demands in reducing the high cassava moisture content of 65 wt% to the low cassava flour required moisture content of 0.1 wt% (Ajiboshin *et al.*, 2011). The observation of drying being the most energy intensive units operation in most food processing facilities also supports the noted finding (Singh, 1986).

In the MF processes, noted energy intensities ranged between 1.96–4.13 MJ/kg. The drying unit operations expended 69.6, 89.2 and 36.1% of the traditional, semi-mechanised and mechanised MF process energies respectively. The milling unit operation accounted for 30.4, 6.0 and 3.1% of the traditional, semi-mechanised and mechanised MF total process energies respectively. Thus the drying unit operation was the most energy intensive followed by the milling unit operation.

Mechanisation provides an energy saving benefit in the CF process, while increasing in energy demands in the MF process and providing no consistent trend (increase or decrease) on the energy demand by the CPO process. The noted inconsistent impact of mechanisation on the considered food processes' energy demands is mainly due to the combination of variations in the process equipment, energy and mass conversion efficiencies of the process equipment, and process energy forms in the referred food processes (Akinoso *et al*. 2013; Jekayinfa and Bamgboye, 2008). Thus, the impact of mechanisation on the energy demands of food processes is dependent on the food process and does not necessarily come with a general advantage of reduction in process energy demands.

The modern energy (diesel and electricity) demands in the crude palm oil, cassava flour and maize flour production processes generally increased with increase in the level of mechanisation of the process. Thus, the suggested high cost of modern energies in the SSA (FAO, 2012) implies increasing the level of mechanisation of the food processes (CF, CPO and MF processes) has a potential consequence of increasing production cost. This observation could be a contributing basis for the assertions that the lack of in addition to costly modern energy in African rural areas contributes to the less adoption of the mechanised food processing technologies (FAO, 2012). On the other hand, adequate biomass residues generated within the food processes could meet the modern energy demand that accompanies the introduction of mechanised units in the processes. Nonetheless, these generated residues are minimally exploited as simple traditional fuel which is combusted in cook stoves for heating purposes. The limitation to harnessing the modern energy potential from the biomass residues (in advancing mechanisation of the food processes) could be attributed to uncertainties of technical and economic feasibilities as applicable energy conversion technologies exist (Ajoku, 2012; Wang, 2009).

4 FEASIBILITY ASSESSMENT OF CONVERTING PROCESS BIOMASS RESIDUES TO IN-HOUSE ENERGY IN CPO MILLS

Summary

The feasibility of supplying the energy demands of a 13 tons fresh fruit bunch (FFB)/hr CPO mill through in-house energy generation from the process solid residues [mesocarp fibre (mf), palm kernel shells (pks) and empty fruit bunches (efb)] and Palm Oil Mill Effluent (POME) was investigated. This was achieved by developing process models entailing flowsheet development, mass and energy balances in Aspen Plus® simulation software. The results of the process models provided inputs for income statement and equipment costing, which were used in the economic assessment of the processes performed in Microsoft Excel. The economic assessments were based on the Ghanaian year 2014 economic context. Three financing structures were assessed: 1. Private investor financing [60% loan and 40% equity from a private investor, having a weighted nominal discount rate of 30%]. 2. The operator of the CPO mill as the investor [60% loan and 40% equity financing by the CPO processor, with an outlook of securing process energy for the CPO mill, as well as making enough cash flow to run the energy facility and pay off loans. Thus, a weighted average nominal discount rate of 14.4%, which was based on 24% interest rate on loan and 0% returns on equity]. 3. Combinations of partial grant and equity (private investor) financing schemes [i.e. investment cost covered by partial grant and the remaining financed by equity, in which the grant component was discounted at 0% and the equity component was discounted at 40% (in nominal terms)].

The CPO mill's energy requirement comprised 40885 tons low pressure steam per year (2.5 bars and 180 °C), 31075 tons hot water per year (80 °C) and 221 kW electricity, thus a Combined Heat and Power (CHP) scheme as an appropriate approach was considered.

Biomass Combustion Steam Turbine (BCST) technology was selected as an appropriate CHP technology for the conversion of solid biomass residue into steam and electricity through in-house energy generation. Such steam turbine CHP technologies have the least power-to-heat ratios of between 0.1-0.3 and thus the most suitable for the mill's low power-to-heat ratio of 0.05. The efb residue with moisture of 65 wt% is less combustible, therefore only the mf and pks residues were used for CHP in-house energy generation, while the efb is

assumed to either be incinerated or used as mulch. The CHP energy generation from only mf and pks (scenario 1) was compared to a second scenario where energy was generated from the mf, pks and efb (scenario 2). In scenario 2, the combustibility of efb was enhanced by shredding and drying to moisture of 45 wt%, through application of excess exhaust steam from the process. Furthermore, energy supply was also supplemented with anaerobic digestion (AD) of the POME to generate biogas and digestate. Gas engine and steam-turbine CHP technologies were identified as appropriate gas CHP technologies that could utilise the biogas for in-house energy generation. The digestate was considered for biofertiliser application purposes in oil palm plantations.

In the solid residues to in-house energy processes, both scenarios 1 and 2 satisfied all the CPO process thermal (40885 tons steam per year and 31075 tons hot water per year) and electric energy (221 kW) demands, with an excess electricity production of 630 and 2280 kW for scenarios 1 and 2 respectively. Thus, the addition of efb to the conventional boiler fuels (Scenario 2) increased the excess electricity for export from 74.0% to 91.1% of the net generated power. The expected power prices for private investor financing were $0.948/kWh (scenario 1) and $0.712/kWh (scenario 2), and under the CPO mill operator as investor were $0.377/kWh (scenario 1) and $0.464/kWh (scenario 2), suggesting the prices for the latter financing scheme were comparable to the prevailing grid power price of $0.348/kWh. On the other hand, at the power price of $0.348/kWh, both scenario 1 and 2 were viable at 80% grant-20% equity and 65% grant-35% equity funding respectively.

In the POME to biogas energy process, the gas-engine route by itself could meet 96.2% hot-water, 5.7% of the steam and 100% of the electrical power demands of the 13 ton FFB/hr CPO mill, while the steam turbine route attained only 28.3% of steam and 22.3% of electric power demands by the CPO mill. Under private investor financing (expected IRR of 30%), the required power prices for economic viability were $0.753/kWh (gas-engine) and $9.403/kWh (steam turbine). Power prices of $0.337/kWh (gas engine) and $3.59/kWh (steam turbine) were required for economic viability under the CPO mill operator (as investor) funding scheme (expected IRR of 14.4%), which suggests the gas-engine route as the only viable option considering the maximum grid price of $0.348/kWh. The steam turbine route was financially viable under 90% grant-10% equity funding, while the gas engine was economically viable at 40% grant-60% equity funding schemes.

4.1 Introduction

Labour intensive and lower production capacities of traditional technologies employed by dominating small-scale processors has been identified as contributing factors for the high shortfall in the potential production capacity of crude palm oil (CPO) in Africa (Zu *et al.*, 2012; Ohimian *et al.*, 2012; Ohimain and Izah, 2013). The industrial scale CPO mill's employ mechanisation technologies, often with medium or large capacity units that could be manual or automated in their operation, which address the referred challenges of the traditional technologies (FAO, 2002). However, both the shortage of supply and cost of electricity and fossil fuels, required to power the mechanized facilities lessens, their adoption (ACET, 2013). Interestingly, the solid biomass residues from the CPO process, comprising palm kernel shells (pks), empty fruit bunch (efb) and mesocarp-fibers (mf), together with its organic liquid waste often termed Palm Oil Mill Effluent (POME) have high potentials for energy generation, to meet the mill's energy demands (Panapanaan, 2009; Yusoff, 2006; Yeoh, 2004). The viability of the in-house energy generation from the referred process residues by CPO mill's, mostly in large scale Southeast Asian facilities, has been demonstrated (Yeoh, 2004; Panapanaan, 2009). However, implementing such in-house energy integration in the growing African CPO industry is limited due to the limited financial benefits and technical feasibility in the relatively small-scale CPO mills in Africa.

In this section, the economic feasibility of converting the solid (mf, pks and efb) and POME residues from the CPO process to energy, to provide for the energy demands of a 13 ton Fresh fruit bunches (FFB)/hr CPO mill, were evaluated. Process and economic models for the in-house conversion of the residues to useful energy sources were developed, based on applicable energy conversion technologies for each residue. The models were developed based on technical data from related literature and conservative assumptions in the event of lack of literature. From the results of the models, the technical and economic performances of the considered technologies were compared to determine the most promising options for the conversion of each residue to energy in the CPO mill.

4.1.1 Overview of Conversion of CPO Mill's Residues to In-house Energy

4.1.1.1 *Conversion of Solid Biomass Residues to CPO Mill's In-house Energy*

It has been suggested that the CPO milling process generates sufficient solid biomass residues, namely palm kernel shells (pks), empty fruit bunch (efb) and mesocarp-fiber (mf), to meet the process energy demands for hot water, steam and electricity (Yusoff, 2006;

Mahlia *et al.*, 2001). It is estimated 0.075 - 0.1 kWh electricity and steam load of about 2.5kg is consumed for every 1kg of CPO produced, translating to a power-to-heat ratio of 0.05, and could be met by combusting 0.3-0.4 kg of the solid residues assuming a boiler efficiency of 100% (Husain *et al.*, 2003). Table 4-1 highlights typical potential for energy generation from of the stated residues in the milling process. In rare cases, the mf and pks residues are used as boiler fuels for the CPO mill's process steam and electricity generation, while the efb is used as mulch or incinerated for its ash as fertilizer supplement in farms (Olisa, 2014; Udoetok, 2012). The inability to utilise the efb as additional boiler fuel has been attributed to its high moisture content of 65 wt%, which reduces its combustibility (Olisa, 2014; Hon, 2010; Evald *et al.*, 2005). However, incineration of efb implies wastage of a renewable energy resource that could provide additional process steam or excess power (Panapanaan *et al.*, 2009). Evald *et al.* (2005) indicated that shredding and drying of the efb to moisture content of 45 wt% could improve its combustibility.

Table 4-1: Potential rate of generation of solid biomass residues in crude palm oil (CPO) mills

Material output	Wet FFB basis		Dry FFB basis	
	tons per hectare	% FFB	tons per hectare	% FFB
FFB	20.08	100	10.6	100
Palm kernel	1.2	6	1.2	11.4
efb	4.42	22	1.55	14.6
pks	1.1	5.5	1.1	10.4
mf	2.71	13.5	1.63	15.4

Source: Yusoff, 2006
NB: FFB – fresh fruit bunch; efb – empty fruit bunch; pks – palm kernel shell; mf – mesocarp fibre

4.1.1.2 *Conversion of Palm Oil Mill Effluent (Residue) to In-house Energy*

Palm Oil Mill Effluent (POME) is a waste stream of Crude Palm Oil (CPO) milling process, which comprises of all the process liquid wastes (sterilizer condensate, clarification wastewater and hydro-cyclone wastewater). POME has a characteristic brownish colloidal suspension, high Biological Oxygen Demand (BOD) of about 100 mg/l, suspended solids, oil and grease and thus environmentally unsafe for direct disposal into water bodies (Chong and Zaharuddin, 1988; Er *et al.*, 2011). Table 4-2 shows typical composition of POME. Saifudin and Fazlili (2009) observed that of all the CPO mill's wastes generated, POME constitutes the most voluminous and ecologically hazardous waste stream. It is estimated that for every 1 ton of crude palm oil extracted from milling, a corresponding 2.5 tons of

POME is generated (Sulaiman *et al.*, 2009). Lim (2010) also reported an average of 0.1 ton POME is generated for every ton of fresh fruit bunch (FFB) processed.

In industrial African CPO mills, treatment of POME for safe disposal is undertaken in ponding systems, which involves simply holding the POME in open ponds of about 3-4 m deep for 40 days to degrade with a resultant lower BOD (about 50 mg/l), making it safe for disposal into water bodies (Daniel *et al.*, 2014; Kyei-Baffour and Manu, 2008; Lim, 1998). Although the ponding system is cheaper and easier to undertake, the emission of methane gas (CH_4), a combustible but potent greenhouse gas, from the ponding systems necessitates treatment systems that can trap the methane for biogas production, which could be used to supplement the CPO mill's energy requirement.

Table 4-2: Typical composition of palm oil mill effluent (POME)

Major Constituents	Composition (wt %)
Moisture	6.9
Crude protein	12.5
Crude lipid	10.2
Ash	14.6
Carbohydrate	29.5
Nitrogen-free extract	26.3
Total carotene	0.019

Source: Aliyu and Zahangir, 2012

Estimates revealed the emission rate of methane from the POME treatment ponds was 1043.1 kg/day/pond (Yacob *et al.*, 2005). Yeoh (2004) observed that anaerobic digestion (AD) of POME at process conditions of 35°C to 55°C corresponds to methane yields between 0.47-0.92 m^3/kg BOD_{added}. Thus AD process, which involves microbial degradation of organic substrate in an anaerobic medium to methane-rich biogas and nutrient-rich digestate, provides a versatile solution to the energy and environmental demands in the oil palm industry. Investigations in few South-East Asian regions revealed that a closed system of anaerobic digestion and digestate application as fertiliser application was feasible for POME processing, with the digestate suitable as an organic fertilizer in oil palm plantations (Tong and Jaafar, 2005; Yeoh, 2004).

4.1.2 Applicable Technologies for the Conversion of the CPO Mill's Biomass Residues to the Mill's Process Energy Forms

Considering that the CPO mill's energy requirement is comprised of low pressure steam (2.5 bars and 180^oC), hot water (80^oC) and electricity, a combined heat and power (CHP) scheme is an applicable approach for conversion of bio-wastes to energy. Demonstrations revealed that, irrespective of the technologies employed, electricity production from biomass is most economical when the resulting waste heat is captured and utilized in thermal applications as in CHP schemes (Bernotat and Sandberg, 2004). Conversion of biomass to usable energies such as power or heat requires appropriate technologies, which depend on factors such as quantity and physical characteristic of the biomass resource, economic conditions and the desired end-use energy forms (McKendry, 2002). For instance anaerobic digesters are suitable for organic waste water or animal wastes, while combustion is more applicable to solid (woody) biomass (Chynoweth *et al*., 2001).

4.1.2.1 *Solid Biomass Combined Heat and Power (CHP) Technologies*

For purposes of CHP applications, solid biomass could be utilized by direct combustion, or converted into combustible gases that can be utilised in gas CHP technologies. The most common conversion approach for solid biomass is direct combustion for subsequent heat transfer to a working medium (heat transporting fluid) that can power a turbine or engine. The working media could be organic oil vapour employed in Organic Rankine Cycles, and helium, hydrogen or air utilised in Stirling engines, or steam employed in steam turbines, with the latter dominating present trends (Kempegowda *et al.,* 2012). Alternatively, the biomass can be converted into a combustible gas via gasification (with the produced gas often called syngas) or anaerobic digestion (where the produced gas is termed biogas), which could power a wide range of CHP technologies such as gas turbines, gas engines and micro gas turbines (US EPA, 2008). Proven, cost-effective CHP technologies for biomass conversion are direct combustion and anaerobic digestion technologies, while gasification technologies are rapidly maturing (Kempegowda *et al.,* 2012; Dong *et al*., 2009).

4.1.2.2 *Gas CHP Technologies*

Gas fuelled CHP technologies utilise syngas or biogas for electricity generation, with waste heat recovery. These range from reciprocating engines (gas engines) to gas turbines, micro-turbines and steam turbines. The choice of gas fuelled CHP technology depends primarily on its end applications. Typical criteria such as power-to-heat ratio, available sizes of technology, CHP installed cost, and operational and maintenance cost (O&M) can be considered in making preliminary selection of technologies for a given CHP duty (US EPA, 2008). Table 4-3 highlights cost and performances of some gas powered CHP technologies.

Table 4-3: Cost and performance characteristics of Combined Heat and Power (CHP) technologies

Parameters	Steam Turbine*	Reciprocating Engine	Gas Turbine	Micro-Turbine
Available sizes (MW)	0.05 - 250	Few KW - 5 MW	0.5 - 250	0.03 – 0.25
Power-to-heat ratio	0.1 – 0.3	0.5 - 1	0.5 - 2	0.4 – 0.7
Uses of thermal output	LP – HP steam	Hot water, LP steam	Heat, Hot water, LP steam	Hot water, LP – HP steam
CHP installed cost ($/kW)	430 - 1100	1100 - 2200	970 - 1300	2400 - 3000
O & M cost ($/kWh)	< 0.005	0.009 – 0.022	0.004 – 0.011	0.012 – 0.025

* For steam turbine, not entire boiler package; LP-low pressure; HP-high pressure.
Source: US EPA, 2008.

4.2 Methodology

4.2.1 Selection of Appropriate Biomass CHP Technologies for the CPO Mill's In-house Energy Generation from Process Residues

4.2.1.1 *CHP Technology Selection for the Solid Residues to In-House Energy Process*

As noted above, solid biomass could be combusted directly or converted into syngas which can then be utilised in CHP schemes. CHP technologies that utilize gases such as gas turbines and gas engines have typical power-to-heat ratios between 0.5-2, whilst that of steam turbines ranges between 0.1-0.3 (US EPA, 2007). From the determined CPO mill's power-to-heat ratio of 0.05 (Husain *et al.*, 2003), indicating a much larger demand for process steam than for electricity, the steam turbine with the least power-to-heat ratios ranging 0.1-0.3 (as seen in Table 4-3) is the most applicable choice. Also, the direct combustion/steam turbine CHP technology is commercially proven and cost effective (Kempegowda *et al.,* 2012). Thus, a Biomass Combustion Steam Turbine (BCST) CHP technology (as shown in Figure 4-1) was considered for the conversion of the CPO mill's solid residues to in-house energy.

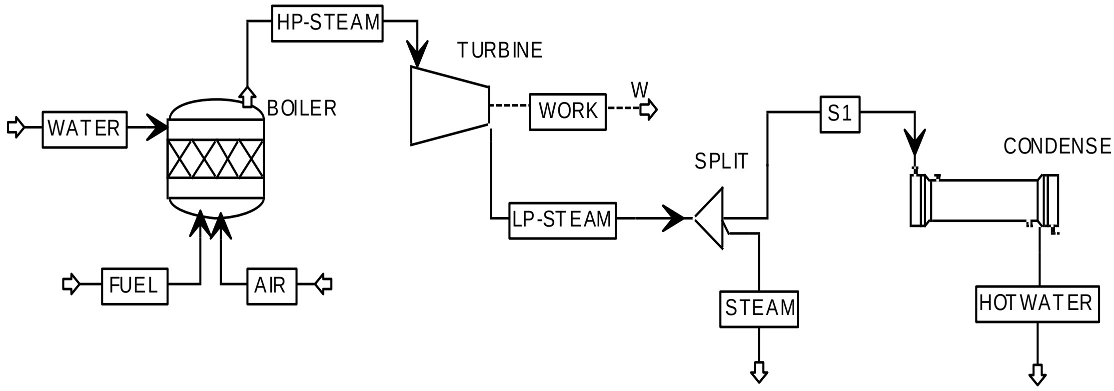


Figure 4-1: Schematic diagram of the Biomass Combustion-Steam Turbine Combined Heat and Power (for Crude Palm Oil in-house energy generation from solid residues) scheme

4.2.1.2 *CHP Technology Selection for the POME to In-house Energy Process*

The cost and performance characteristics of gas fuelled CHP technologies summarised in Table 4-3 were considered in selecting an appropriate choice for the POME to in-house energy process. The sizes of the technologies were considered as an initial selection criteria. Yeoh (2004) suggested large scale CPO mills with POME loads of 240 m^3/day-450 m^3/day produced enough biogas to generate about 0.626-0.965 MW of power using a gas engine generator. Taking this as a basis, the 181 m^3/day POME for the 13 tons FFB/hr mechanised CPO facility under study is expected to generate less than 0.5 MW power hence ruling out gas turbines as a realistic option. Also, the high O&M and installed cost of micro-turbines as compared to those of steam turbines and reciprocating engines ruled out micro turbine as an option considering the intended application is in low income earning rural settings. Given the required thermal energy forms of the CPO mill being low pressure (LP) steam (2.5 bars and 180°C), hot water (80°C) and a power-heat-ratio of 0.05 for CPO mills, steam turbines and gas engines are ideal choices as indicated in Table 4-3 hence the selected choices for consideration.

4.2.2 Developing the Aspen Process Models for the CPO solid Residue to In-house Energy Processes

The models for the processes to convert biomass residues to in-house energy sources, involving process flow sheet with mass and energy balances, were developed in Aspen Plus®

simulation software (Aspen Technology, Inc.). The CPO mill's process conditions adopted in the modelling were from related literature as summarized in Table 4-4.

Table 4-4: Crude Palm Oil mill's process conditions adopted in this study

Process parameters	Adopted conditions	Reference
Plant Capacity	13 tons FFB/hr	Kyei-Baffour and Manu, 2008
Process steam	0.42 ton/ton FFB (2.5 bar and 140°C)	Sommart and Pipatmanomai, 2011; Mahlia et al, 2001)
High pressure steam	32 bar and 400°C	Sommart and Pipatmanomai, 2011
Process hot water	This study's estimate of 0.32 ton/ton FFB (0.47 bar and 80°C)	Mahlia et al, 2001
Electricity	17 kWh/ton FFB	Sommart and Pipatmanomai, 2011

4.2.2.1 *CPO Mill's Solid Residues Conversion to In-House Energy Process Modelling Basis and Approach*

The solid residue to the in-house energy facility was modelled as a stand-alone facility adjoined to the CPO mill, which supplied the thermal and electric energy demand of the mill. An operational period of 24 hrs/day and 312 days/yr, the same operational period of the referred CPO mill, was assumed. The conventional energy scheme from mf and pks (scenario 1), and that of suggested energy generation from mf, pks and efb (scenario 2), as described in Figure 4-2 and Figure 4-3 respectively, were considered under this study. In Scenario 2, the combustibility of EFB was enhanced by shredding and drying to a moisture content of 45 wt% utilizing excess exhaust steam from the steam turbine.

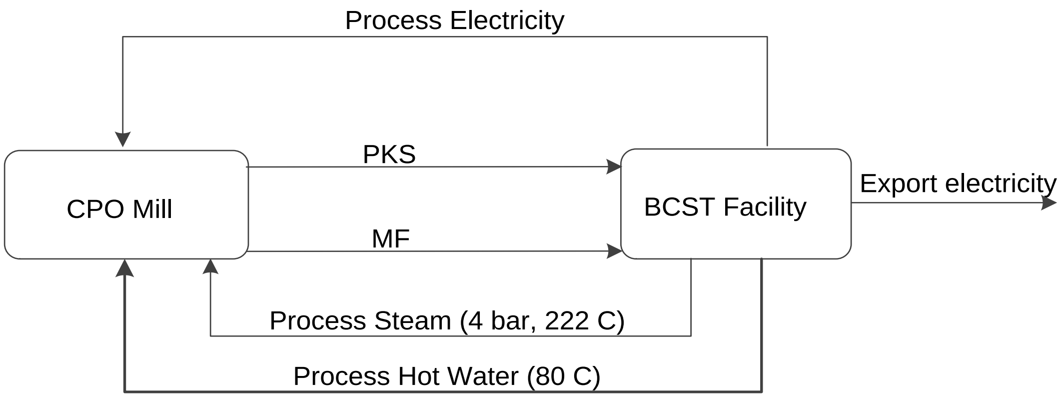


Figure 4-2: Block flow diagram of conventional crude palm oil mill in-house energy generation from solid residues scheme (without empty fruit bunch residue addition)

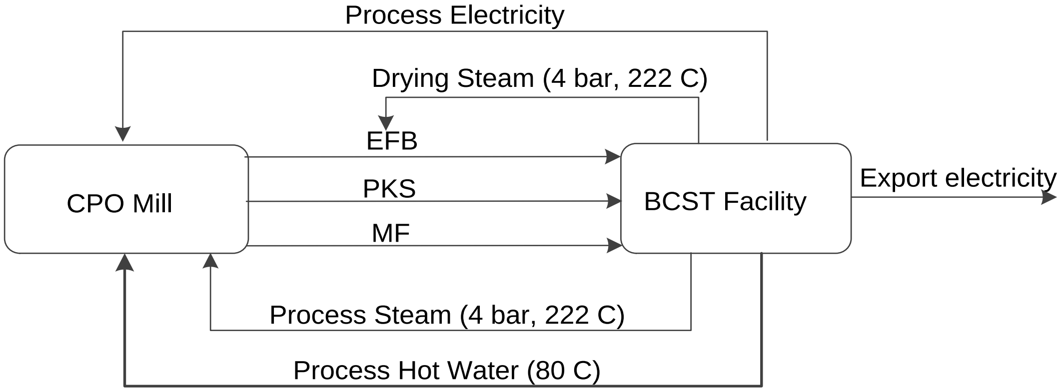


Figure 4-3: Block flow diagram of suggested crude palm oil mill in-house energy generation from solid residues scheme (with empty fruit bunch residues addition)

In the Aspen Plus® process models, the highest possible energy recovery from exhaust streams was ensured, to minimize energy losses from the process. Design specification functions were introduced to ensure the total boiler feed water flowrate was just enough to meet the CPO process steam and hot water demand, and empty fruit bunch (efb) residue's drying steam in scenario 2. High pressure steam from the boiler was specified at 35 bar and 400°C (Sommart and Pipatmanomai, 2011). Exhaust steam from the steam turbine was specified at 4 bar and 222.7°C, to account for transmission energy and thermal losses as the actual required CPO process steam conditions were 2.5 bar and 180°C (Sommart and Pipatmanomai, 2011). The turbine discharge steam was split into the process steam, EFB dryer steam (scenario 2) and the remaining portion condensed to hot water (at 80°C) to the CPO process. The boiler feed water was used as the cooling water (thus preheated) to condense the steam to hot water. The boiler flue gas (discharged to the atmosphere at 120°C) was used to preheat the combustion air from 37°C to 250°C prior to its discharge to the atmosphere, by means of a heat exchanger. Combustion air was supplied in excess of 40% to ensure complete combustion as well as to attain environmental regulations regarding allowable flue gas composition (Mbohwa, 2003). Furthermore, the components of the biomass residues (mf, efb and pks), being complex and not readily available in the Aspen plus® property database, were introduced as their lignocellulosic components (shown in Table 4-5) following similar protocols in the work of Humbird *et al.* (2011).

Table 4-5: Lignocellulosic components of CPO mill's solid residues adopted in this study

Components	efb[1]	mf[2]	pks[3]
Cellulose	59.7	42	29.7
Hemicellulose	22.1	32	16.9
Lignin	18.1	22	53.4

N.B: All given values are in weight percentage (dry basis)

[1] Abdullah *et al.*, 2011; [2] Nordin *et al.*, 2013; [3]Arami-Niya *et al.*, 2010

4.2.2.2 *POME to In-house Energy Process Modelling Basis and Approach*

An operational time of 24 hrs/day and 300 days/year was assumed for the process (Yeoh, 2004). Anaerobically digested POME is an adequate organic fertilizer in oil palm plantations with significant benefits of 10-23% increase in FFB yield (Lim, 1988; Yeoh, 2004). Therefore, the CPO mill was assumed to be situated in close proximity to an oil palm plantation, which utilise the digestate as fertiliser (land applications) via bed and sprinkler systems (Yeoh, 2004; FAO, 2002). In the process modelling, the entire process was sectioned into 3 main hierarchies: Anaerobic digestion process, Biogas cleaning process and CHP process which are briefly described below.

Anaerobic Digestion Process

This hierarchy involved the Anaerobic Digestion (AD) process of POME to biogas and digestate. The AD process is driven by sensitive microorganisms hence requires pre-treatment of the POME to ensure conditions for optimum performance of the process. Freshly discharged POME from the CPO mills is initially retained for a day in a holding pond for de-oiling, followed by cooling to the thermophilic AD temperature of 55°C, which results in high biogas yields, before being taken through an acidification process in a separate pond for a retention time of 5 days (Yeoh, 2004). The treated POME is then pumped to a sludge sedimentation feeding tank and finally distributed to the AD reactor by means of a distribution system, which ensures homogenisation and uniform feed conditions.

Due to the complex nature of the AD process and the lack of literature on the required input parameters for the components of POME in Aspen Plus® database, the entire AD process was modelled as a black-box in the Aspen simulation. The AD process conditions, equipment and energy requirements as well as biogas yield were based on the study by Yeoh (2004). The hydraulic retention time (HRT) and the volume of the digester (V_T), the critical AD operating parameters, depended on the substrate load as shown in Equation 14. Thus for the reaction kinetics to be the same as that of the adopted study, the HRT was maintained at the determined average of 10.2 days. Hence the effective reactor (digester) was resized for this study's estimated POME load of 181.85 m^3/day. The estimated parameters are summarised in Table 4-6.

$$\mathrm{HRT} = \frac{V_T}{V} \tag{14}$$

Where: HRT is hydraulic retention time (days)

V_T is digester volume (m^3)

V is volume of substrate fed per unit time (m^3/day)

Table 4-6: Estimated process and operating conditions for the Palm Oil Mill Effluent Anaerobic digester based on the study by Yeoh (2004)

Parameters	Parameters from Yeoh (2004)	Estimates for this study
Design Basis		
POME load (m^3/day)	240 - 450	182
Operating Parameters		
Digester temperature (^oC)	55	55
Minimum effective reactor volume (m^3)	3200	1855
HRT (days)	13.3 - 7.1	10.2
Biogas production rate ($m^3 m^{-3}$ day^{-1})	2.65 - 4.96	3.81
Annual biogas production rate (m^3/yr)	3.94×10^6	2.12×10^6

Biogas Purification Process

The intended use of the generated biogas and its composition determines the necessity of purifying the biogas. Typical average composition of biogas from AD of POME reported was 64 % vol. CH_4, 36 % vol. CO_2 and 670–2500 ppmv H_2S (Quah and Gilles, 1981). According to Tong and Jaafar (2005), for sophisticated applications such as vehicle fuel, the biogas has to be scrubbed of unwanted gaseous components to typical compositions of 97% CH_4, below 3% CO_2, below 10 ppmv H_2S and water content below 32 mg/Nm^3. However, considering steam boilers and gas engines are relatively less sensitive to water and CO_2 components, the scrubbing of the gas was attentive on reducing the corrosive and toxic H_2S component of the biogas to a safe limit of below 1000 ppm (Tong and Jaafar, 2005). The technology employed was water scrubbing due to the ease of accessing water in the intended rural locations. In the Aspen plus® process modelling, the scrubber was modelled as a RadFrac column. A design specification was introduced to specify the water flowrate at conditions resulting in mass fraction recovery of 0.99 H_2S in the scrubber effluent stream. It was ensured that the CH_4 content absorbed by the scrubber effluent did not exceed 0.6 wt%. Economical means for treatment of H_2S waste water include air dosing (aeration) and iron chloride methods (Chambers and Potter, 2002). The air dosing method involves exposure of the H_2S waste water to atmospheric air which facilitates reaction between the oxygen in the air and H_2S to form an odourless, dissolved sulphate. In the iron chloride method, ferric chloride ($FeCl_3$) is added to the H_2S waste stream, which reacts to form FeS precipitates that can be filtered out of the waste water. Treatment and disposal of the H_2S scrubber waste water (effluent) was considered as a peripheral process that was not modelled in this study. Nonetheless, the operational cost for the H_2S treatment facility was evaluated as part of the total waste treatment cost estimate of 2.5% of TOC for the POME-to-in-house energy process (Yeoh, 2004), while the equipment for treatment is presumed to be covered in the allocated contingency of 10% of the Total Direct Cost (as shown in Appendix B8) in the estimation of the Total Capital Investment (Humbird *et al.*, 2011).

CHP Process with biogas

As aforementioned, the two CHP technologies investigated for the POME to in-house energy process were gas-engine and steam turbine. The Aspen Plus® process modelling approaches of the referred CHP technologies are briefly described below.

Gas-engine route

According to literature, the available thermal energy from gas-engines ranged between 60-70% of the inlet fuel's energy content which is obtained from the exhaust gas and coolant streams (engine jacket cooling water, lube oil cooling water and turbocharger cooling) (US EPA, 2008). In CHP applications, the hot exhaust gas which constitute about half of the available thermal energy is ideal for generation of high pressure (HP) steam up to 10.4 bars. The remaining thermal streams are at relatively low temperatures with suitable applications in low pressure (LP) steam (below 2 bars) or hot water generation. Also, in the combustion chamber of the gas engine, compressed fuel-air mixture ranging from stoichiometric ratios up to moderately lean mixtures is directly injected into the chamber and ignited by an exposed tip of a spark plug (US EPA, 2008).

Taking all the above as a basis, the gas-engine generator was modelled as a combustion reactor (RStoic) and a turbine in Aspen Plus® as there was no conventional unit for gas engines. In the modelling, the combustion air was compressed to 4 bars and its flowrate was set to 40% excess of the stoichiometric ratio required to completely combust the CH_4 component of the biogas, so as to ensure environmental regulations regarding allowable flue gas composition are attained (Mbohwa, 2003). The flue gas from the combustion chamber was fed into the turbine. The turbine's discharge stream's energy was controlled to be 65% of the energy content of the biogas fed by means of a multiplying block set to a multiplying factor of 0.563. The turbine exhaust stream was then split into two equal streams (representing the hot exhaust gas and the hot coolant streams) with both having the same thermal energy as the exhaust gas stream is one half of the available thermal energy. The hot exhaust gas and the hot coolant streams were then utilized in CPO process steam (4 bars and 185.6°C) and hot water (80°C) generation respectively by means of conventional heat exchangers.

Steam turbine route

In the steam turbine CHP route, the major units modelled in Aspen Plus® were the steam boiler, steam turbine and generator. The boiler was modelled as a combustion chamber and steam generation chamber in which heat is recovered from flue gases after combustion of the biogas in a combustion chamber (RStoic) and utilized in producing HP steam (32 bars and 400°C). The combustion air was compressed from atmospheric conditions to 1.72 bars and preheated with discharged boiler flue gases to 211.7°C. To ensure convergence and ease of simulating a typical steam boiler, the steam generation chamber was modelled as three heat exchangers in series representing the process heating side through which the flue gases were passed. Heat was extracted from each heat exchanger to corresponding heat exchangers also connected in series through which boiler water was pumped until the discharged flue gases was at 350°C. The amount of HP steam produced is limited by the targeted steam quality, therefore a design specification function was introduced to control the water flowrate that results in the required HP steam conditions of 32 bars and 400°C. The generated steam was then fed to a steam turbine modelled as a turbine with an efficiency of 72% and its discharged pressure specified at 4 bars to account for transmission energy and losses as the required CPO process steam pressure was 2.5 bars. To account for the generator's impact on the electricity generated, the network output from the turbine was reduced by a multiplying block with a multiplication factor of 0.98 which corresponds to the typical efficiencies of generators (US EPA, 2008).

4.2.3 Technical Performance Assessment of the CPO Mill's In-house Energy Processes

The energy processes' technical performances were evaluated in terms of their energy efficiencies. Overall CHP efficiency (as described in Equation 15) was the technical performance criteria considered. All steam, hot water and electricity generation rates were obtained directly from the Aspen Plus® simulation results.

$$\eta_{\text{overall}} = \frac{E_{\text{elec power}} + E_{\text{th process}}}{E_{\text{th biomass residue}}} \tag{15}$$

Where: $E_{\text{elec power}}$ is net electric power output (MW)

$E_{\text{th process}}$ is net thermal energy output (MW_{th})

$E_{\text{th biomass residue}}$ is thermal energy in the input biomass fuel (MW_{th})

The net thermal energy output was determined as the difference between thermal energy of all thermal products (CPO mill's process steam and hot water) and the thermal energy input to the energy process (energy content of boiler feed water). Net electric power output was obtained by subtracting the sum of all power utilized by the CHP process' equipment such as compressors and pumps from the gross electricity output. In determination of the net electric power output for the POME-to-energy process, the power required in generating the biogas (anaerobic digester) was not considered, however the power demand in cleaning the biogas was included in the process power demands as it was assumed scrubbing of the biogas occurs at the CHP section of the facility. The solid residues (biomass fuel) energy was estimated as the sum of energy contents of all the input biomass residues based on their LHV given in Table 4-7.

Table 4-7: Lower Heating Values (LHV) of biomass residues adopted in the CPO mill in-house energy process modelling

Biomass residues	LHV (MJ/kg)
EFB (60 % moisture)	5.50
MF (40 % moisture)	9.90
Palm Kernel Shell (10 % moisture)	17.10
Source: Panapanaan *et al.*, 2009	

4.2.4 Economic Assessment of the CPO Mill in-house Energy Processes

The generated mass and energy data from the developed process models provided input variables for income statements and cash flow statements. The process flow sheets provided the equipment data which was used for sizing and costing of the equipment in the balance sheet development. The income statements, cash flow statements and balance sheets were then used to generate the economic models of the processes performed in Microsoft Excel.

Economic feasibility evaluations inform investors of financial risks/benefits of investing money into a project and as such vital for investment decision making. As capital investment is made at the beginning of a project but profits are expected at later periods by which the real monetary value (investment period value) has diminished, some economic viability indicators [Net Present Value (NPV) and Internal Rate of Return (IRR)] take into account the discounted time value of money (often termed the discounted cash flow rate of rate, DCFROR). DCFROR is undertaken by introducing a discount rate (which represents the rate of diminish in value of the returns) and performed on the cash flow sheet built from the Total Capital Investment (TCI) and Total Production Cost (TPC). Other economic viability indicators [such as Return on Investment (ROI) and Payback Period (PB)] do not consider the time value of money but help in quick decision making. Thus in all profitability assessments in this study, NPV, IRR and PB were the considered economic viability indicators. These viability indicators are briefly discussed below based on definitions from Lauer (2008):

- NPV gives an indication of the returns on investment of a project over the project period in present (investment period) monetary value terms. It is determined by discounting the cash flows (net earnings) for each year to present monetary value, summing them up over the project period followed by subtracting the capital investment from the obtained sum. A positive NPV implies the project value increases by that amount over the capital investment in present monetary value. An NPV of zero denotes the investment has been recovered over the project period with no losses or a gain which is often termed break-even. A negative NPV implies the project is not feasible taking into account the discount rate considered.
- IRR is the discount rate which results in an NPV of zero. Thus it is the average annual return rate on the initial capital investment over the project period that results in break-even. From an investor's perspective, an attractive project should have less financial risks. Hence, the IRR value is often benchmarked against the

interest rate of banks as investments in banks are deemed less risky with assured returns. An IRR greater than the prevalent interest rate results in a positive NPV implying a viable project whereas an IRR less than the interest rate yields a negative NPV denoting an unprofitable project. Thus the greater an IRR is over the prevailing interest rate, the greater the returns on the project's investment.

- Payback period is the time period at which the initial original capital investment is expected to be recovered and does not consider the time value of money.

As noted, performing the DCFROR analysis demands considerations of certain economic conditions such as tax rate, interest/discount rate and plant life. Hence, the economic models were based on Ghana's 2014 economic conditions. Net Present Value (NPV), Internal Rate of Return (IRR) and Payback-period, considered as the economic performance indicators, were based on a plant life of 25 years for the solid residue to in-house energy facility (IRENA, 2012a) and 15 years for the POME to in-house energy facility (Muradin and Foltynowicz, 2014). Three financing structures were investigated:

- Private investor financing structure: This approach considered a finance scheme of 60% loan and the remaining 40% equity from a private investor (i.e. not the CPO mill operator). Future monetary projections considered a weighted average nominal discount rate of 30%, which was based on 24% interest rate on loan (BoG, 2014) and an assumed 40% returns on equity.
- The operator of the CPO mill as the investor: This structure evaluated a finance scheme of 60% loan from banks and 40% equity financing by the CPO mill processor, with an outlook of securing process energy for the CPO mill and making enough cash flow to run the energy facility and pay off loans (but not for profit purposes). Thus, future cash flow projections were evaluated at a weighted average nominal discount rate of 14.4%, which was based on 24% interest rate on loan (BoG, 2014) and an assumed 0% returns on equity.
- Combinations of partial grant and equity (private investor) financing schemes, i.e. the investment cost was covered by partial grant and the remaining cost financed by equity, in which the grant component was discounted at 0% and the equity component was discounted at 40% (in nominal terms).

In the economic assessments for all the financing schemes, cash flows were inflated at an annual inflation rate of 15% (BoG, 2014). Annual income tax rate was specified at the general corporate tax rate of 25% and was charged on only positive taxable income (GRA, 2014). Baseline economic scenarios were based on prevailing grid power prices of $0.207 (between 0-100 kWh) and $0.348 (above 600 kWh) (PURC, 2014). Assumptions considered in estimation of the TCI for the energy processes are summarised in Appendix B8. Operating labour costs were estimated based on minimum wage of $2.106/day as of 1st April, 2014 (GSS, 2008) or obtained from available labour cost data (www.mywage.org). Plant maintenance cost was evaluated as 3% of total installed plant cost (Humbird *et al.*, 2011). Overhead cost was estimated as sum of income tax (25% of net revenue), labour burdens (10% of operating labour), and property insurance (0.7% of fixed capital investment) (GRA, 2014; Humbird *et al.*, 2011).

In the income statements, it was assumed the net power and thermal energy generated by the energy facilities would be sold to the CPO mills and excess power if available would be sold as export electricity. In the solid residues to in-house energy process, the biomass feedstock (CPO solid biomass residues) was assumed to be purchased from the CPO mills. The prices of the biomass feedstock were estimated as their energy equivalent price of firewood at $0.01/MJ (Energica, 2009) (see details in Appendix B3). This was based on the assumption that the means of transportation and its impacts on the price of firewood is envisaged to be similar to that for the biomass feedstock (Ndegwa *et al.*, 2011; Lambe *et al.*, 2015). On the other hand, for the POME to in-house energy process, the POME was assumed to be obtained from the CPO mill at no cost as its treatment cost is indirectly incurred by the energy facility. The revenue from the digestate as fertiliser for the oil palm plantations was estimated as the economic value of the net increase in the yield of fresh fruit bunch (FFB).

4.3 Results and Discussion

The detailed process flowsheets developed in Aspen Plus® software for the solid residues to in-house energy processes and POME to in-house energy processes are given in Appendix A1-A2 and Appendix A3-A4 respectively. Their respective economic parameters are presented in Appendix B3 and B4.

4.3.1 Technical and economic performances of the CPO mill's solid residues to in-house energy Process models

4.3.1.1 *Technical Performance of the CPO Mill's Solid Residue to In-House Energy Process Models*

Table 4-8 summarises the technical performance results of the solid residues to in-house energy processes. From the result in Table 4-8, it can be noted that in both scenarios 1 and 2, the considered biomass residues were sufficient for all the CPO process energy demands [40885 tons steam/year, 31075 tons hot water/year and 221 kW electricity] with excess electricity of 630 and 2280 kW for scenarios 1 and 2 respectively. Thus, the addition of EFB to the conventional boiler fuels (Scenario 2) increases the excess electricity for export purposes from 74.0% to 91.1% of the net generated power when compared to Scenario 1 (with no efb addition to the boiler residues).

Table 4-8: Estimated rate of generation of crude palm oil mill's solid residues and Technical performance of the solid residues to in-house energy processes

Rate of generation	Scenario 1	Scenario 2
Mf[1]	13141	13141
pks[1]	6837	6837
efb[1]	-	45576.46
CPO Process steam[1]	40885(100)[3]	40885(100)[3]
CPO Process hot water[1]	31075(100)[3]	31075(100)[3]
efb drying steam[1]	-	161841
CPO process electricity[2]	221(100)[3]	221(100)[3]
Export electricity[2]	630	2280
Overall CHP efficiency (%)	70.2	55.1

[1]expressed in tonnes per year; [2]given in kW; [3]Values in parenthesis represents percentage of energy demand of the 13 ton FFB/hr CPO mill attained

In addition, 0.127 kWh power & 1.44 kg steam (Scenario 1) and 0.114 kWh power & 1.42 kg steam (scenario 2) were generated from 0.4 kg of the biomass residues (estimated from results presented in Table 4-8. These estimates compare fairly with estimations of 0.3-0.4 kg of CPO solid residues generating 0.075-0.1 kWh power and 2.5 kg steam assuming a boiler efficiency of 100% reported by Husain *et al*. (2003). The higher electric power and lesser steam obtained in this study are as a result of the high waste heat recovery and lower boiler efficiency of 85% employed in the modelling (US EPA, 2007).

As described in Equation 15, the overall CHP efficiency illustrates the effectiveness of the energy process performance in converting available biomass energy to the required electric power and thermal energies. The overall CHP efficiencies of 70.2% for scenario 1 compares well with typical ranges of 70 to 80% for biomass-fired boiler/steam turbine CHP systems (US EPA, 2007). On the other hand, scenario 2's low CHP efficiency of 55.1% could be attributed to the EFB drying (from moisture of 65 to 45 wt%) energy sourced from thermal energy (steam) generated in the CHP process. Hence the BCST CHP process as modelled in this study is energy efficient and simulates typical CHP processes.

4.3.1.2 *Economic Performance of the CPO Mill's Solid Residue to In-House Energy Process Models*

Capital Investment of the CPO Mill's Solid Residue to In-House Energy Process Models

The Total Capital Investment (TCI) and Specific Capital Investment (SCI) for the solid residues to in-house energy process models are shown in Figure 4-4 with the latter reported on the basis of electric power capacity ($/kW). TCI of $17.152 million and $34.859 million were estimated for scenarios 1 and 2 respectively (see Figure 4-4). The obtained SCI of $18440/kW and $12797/kW for scenario 1 (capacity of 0.93 MW) and scenario 2 (capacity of 2.72 MW) respectively compare well with updated estimates of $14948/kW and $4042/kW for similar Biomass Combustion Steam Turbine (BCST) CHP facilities of 0.5 MW and 8.8 MW capacities respectively (IRENA, 2012a). The SCI show a significant impact of economies of scale on the BCST CHP process with a reduction of 30.6% in the TCI of scenario 2 with a capacity of 2.723 MW as compared to that of scenario 1 at 0.93 MW.

The biomass combustion and steam generation section (boiler section) contributed 36.5 and 37.1% of TCI in scenario 1 and 2 respectively, and the turbine CHP section accounted for 10.4 and 9.8% of the TCI in the former and latter respectively (see Figure 4-4). On the basis of installed equipment cost of $9.103 million and $18.522 million for scenarios 1 and 2 respectively, the boiler and turbine CHP sections accounted for 68.8 and 19.7% for scenario 1 respectively, and 69.9 and 18.4% for scenario 2 respectively suggesting the boiler section as the most expensive section of the BCST CHP process.

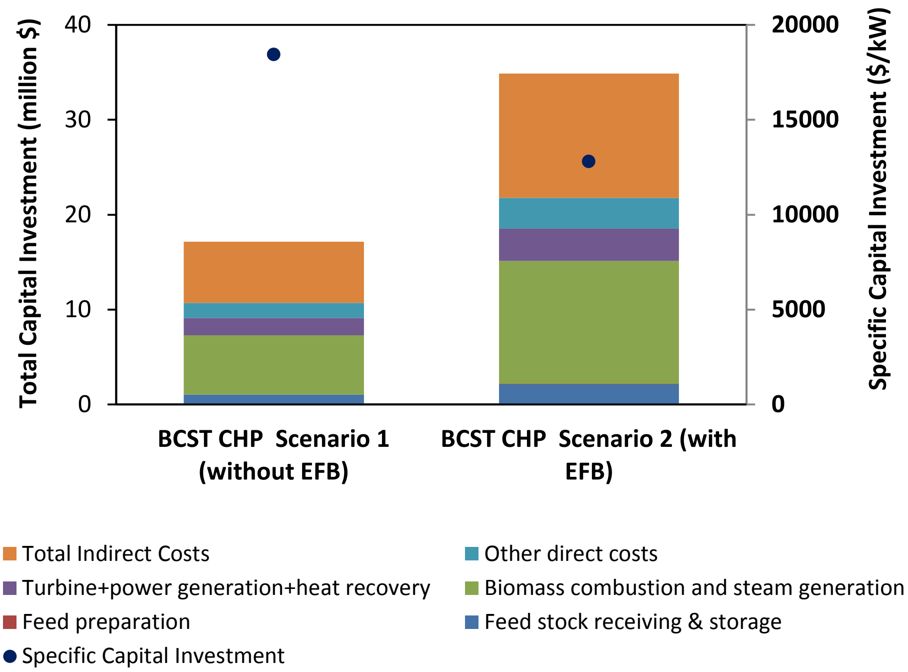


Figure 4-4: Breakdown of Total Capital Investment for crude palm oil mill's solid residues to in-house energy process models

Operating Costs of the CPO Mill's Solid Residue to In-House Energy Process Models

Figure 4-5 highlights the annual Total Operating Cost (TOC) and Specific Operating Cost (SOC) of the solid residues to in-house energy processes as modelled under the study. The operating cost of power facilities are known to be dependent on the power output of the system and as such SOC was expressed on per kWh basis (IRENA, 2012a). The result (Figure 4-5) shows annual TOC estimates of $2.855 million and $5.355 million for scenario 1 and 2 respectively suggesting scenario 2's TOC is higher than that of scenario 1 by 46.7%. However, SOC's of $0.410/kWh and $0.263 kWh for Scenario 1 and 2 respectively (shown in Figure 4-5) suggest scenario 2's SOC is lesser by 36% when compared to the SOC of scenario 1.

In addition, the referred SOC's for scenario 1 (capacity of 0.930 MW) and 2 (capacity of 2.723 MW) translate to $3069/kW and $1965/kW respectively, which are higher than adjusted SOC estimate of $942/kW for a similar sugar mill Back Pressure Steam Turbine CHP facility with a capacity of 21.42 MW in South Africa (Nsaful, 2012). Although operating costs are highly dependent on local economic conditions, a benefit of economies of scale is noted. For instance, the lower SOC in scenario 2 as compared to that of scenario 1 could be attributed to benefits of economies of scale favouring larger capacities as the additional labour requirement for the feedstock (efb) preparation process does not increase the TOC significantly, although the capacity increased significantly. The specific operation and maintenance costs (O&M) of \$0.0298/kWh and \$0.0118/kWh for scenarios 1 and 2 respectively (estimated from results presented in Figure 4-5) implies that the former scenario's O&M was higher by 60.5% than the latter's, which indicates the significant contribution of the O&M to the impacts of economies of scale on the process operating cost.

The costs of the biomass feedstock accounted for 80.9% and 86.9% of the TOCs for scenario 1 and 2 respectively (Figure 4-5), which indicated the operational cost of the energy processes was highly reliant on the feedstock costs. The high incidence of feedstock costs on the TOC is comparable to the incidence of feedstock price on TOC (80.2-86.7% of the TOC) for a similar sugar mills' biomass CHP process in South Africa (Nsaful, 2012). Feedstock prices are highly influenced by factors such as transportation, availability, and competing uses of the feedstock (Ruth *et al.*, 2013). Consequently, it can be inferred that similar high impact of transportation on feedstock price, as observed for firewood in SSA (Lambe *et al.*, 2015; Ndegwa *et al.*, 2011), supports the observed incidence of feedstock price on TOC for the energy processes in this study.

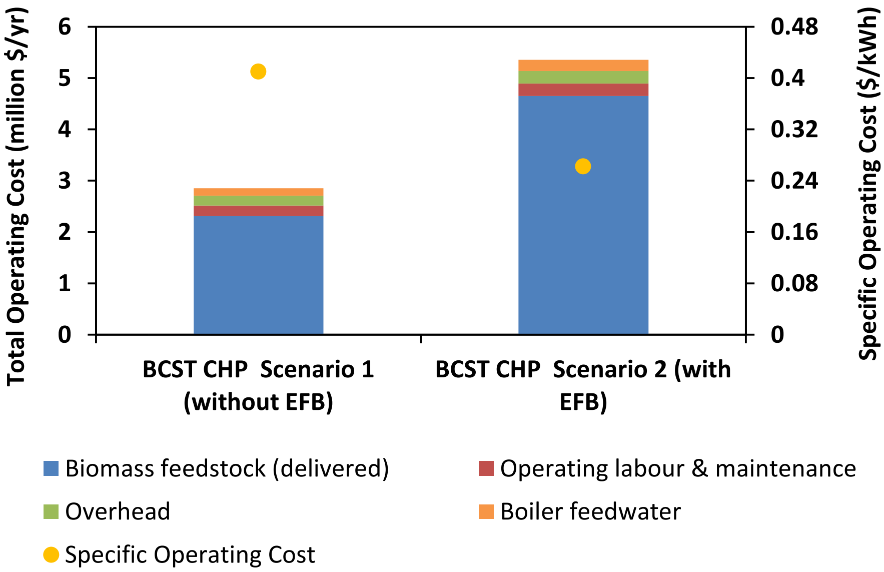


Figure 4-5: Total and Specific Operating Costs for the crude palm oil mill's solid residues to in-House energy process models

4.3.1.3 *Profitability Assessment of the CPO Mill's Solid Residues to In-House Energy Processes*

The results of the profitability assessment for the solid-residues to in-house energy, under private investor financing [60% loan (at 24% interest rate) and 40% equity (at 40% interest rate), having weighted nominal discount rate of 30%] are summarised in Table 4-9. In the economic assessment, all net products from the BCST facility (CPO process steam, CPO process hot water, CPO process electricity and export electricity) were considered as revenue sources with the steam and hot water at estimated prices of $0.0397/kg and $0.0129/kg respectively (see details in Appendix B3). From the results (given in Table 4-9), neither scenarios 1 nor 2 attained the expected minimum IRR of 30% (based on weighted average discount rate of 30%) at the base-case power prices of $0.2073/kWh and $0.348/kWh. Nevertheless, Scenario 2 improved the economic performance marginally by 1.3–3.0% increase in the IRR when compared to scenario 1.

Table 4-9: Private investor financing results for the crude palm oil mill's solid residues to in-house energy process models

Parameters	Electricity s.p. of $0.207/kWh		Electricity s.p. of $0.348/kWh	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
NPV (million $)	-27.97	-55.91	-22.04	-38.85
IRR (%)	0.1	1.4	9.9	12.9
Payback period (yrs)	24.8	23.2	15.5	13

Table 4-10 shows the profitability assessment results for the CPO mill operator investor financing [60% loan (at 24% interest rate) and 40% equity (at 0% interest rate), having weighted nominal discount rate of 14.4%]. The results (given in Table 4-10) were similar to those of the private investor financing scheme (see Table 4-9) and suggest all the processes remained unviable for the expected IRR of 14.4% (based on the weighted discount rate of 14.4% for the CPO mill operator financing). However, scenarios 1 and 2 attained IRRs of 9.93 and 12.925 at the maximum prevailing power price of $0.348/kWh, suggesting the processes are promising when the expected IRR of 14.4% is taken into consideration.

Table 4-10: CPO mill operator (as investor) financing scheme's results for the crude palm oil mill's solid residues to in-house energy process models

Parameters	Electricity s.p. of $0.207/kWh		Electricity s.p. of $0.348/kWh	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
NPV (million $)	-30.25	-58.70	-13.30	-9.78
IRR (%)	0.1	1.4	9.9	12.9
Payback period (yrs)	24.8	23.3	15.5	12.8

Figure 4-6 shows the minimum expected power prices for the solid residue energy processes under funding terms of private investor (nominal discount rate 30%) and CPO mill operator as investor (nominal discount rate of 14.4%) financing schemes. From the result (Figure 4-6), the minimum power prices for the private investor financing scheme were higher than those for the CPO mill investor scheme by 51% for scenario 1 and 47% for scenario 2. Also, under the CPO mill operator financing, the minimum expected power prices of $0.377/kWh (scenario 1) and $0.464/kWh (scenario 2) were 25% and 7.7% higher than the maximum grid power price of $0.348/kWh (see Figure 4-6). For the private investor financing, the minimum expected power prices of $0.948/kWh and $0.712/kWh for Scenario 1 and 2 (respectively) exceeded the maximum grid power price of $0.348/kWh by 63.3% (Scenario 1) and 51.1% (Scenario 2) (see Figure 4-6). Ghana's present national grid power is predominantly from hydro facilities (52%) and fossil fuelled thermal power plants (47.9%) (VRA, 2014). Considering the generated electricity is from biomass (bioelectricity), which is a renewable energy resource (green energy), its actual selling price is expected to be higher than conventional fossil based electric power to reflect its environmental contributions. Leibbrandt (2010) indicated safe assumptions of 20% increment can be made in estimating the selling price of a bioelectricity from a fossil based power price to account for the environmental contributions. Hence, under consideration of environmental contributions of the bioenergy processes, only the CPO mill's operator funding scheme for scenario 2 is economically viable (see Figure 4-6).

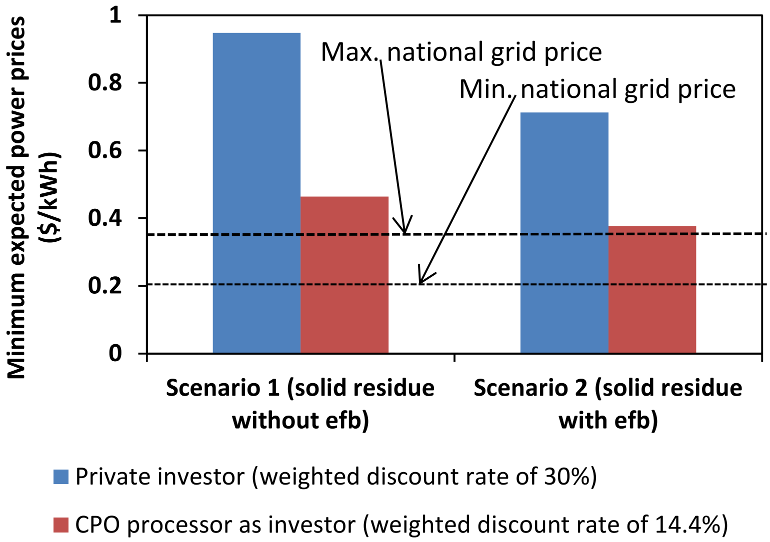


Figure 4-6: Minimum expected power prices for solid residues to energy processes, for private investor (discount rate of 30%) and operator of the CPO mill as investor (discount rate of 14.4%) financings structures

Figure 4-7 shows the minimum expected CPO mill's power prices (with an assumption of all surplus generated power being sold at prevailing grid price of $0.348/kWh) for the private investor financing and CPO mill operator investor financing. From the results (Figure 4-7), financing of the energy facility by the CPO mill operator requires minimum power prices of $0.795/kWh and $0.679/kwh for scenario 1 and 2 (respectively) to be viable. On the other hand, the minimum power prices required for the private investor financing (discount rate of 30%) to be viable were $3.204/kWh (scenario1) and $5.58/kWh (scenarios 2) (Figure 4-7). These findings suggest only the minimum expected power prices under the CPO mill investor financing had the same order of magnitude as the prevailing grid power prices ($0.207/kWh and $0.348/kWh).

The impacts of the referred minimum expected CPO mill's power prices, with an assumption of all surplus generated power being sold at prevailing grid price of $0.348/kWh, on the profitability of the CPO milling process (minimum expected IRR of 30% for viability) were analysed by determining their resulting CPO mill's IRRs (presented in Figure 4-7). The minimum expected power prices for scenario 1 and 2 under the CPO mill operator investor financing corresponded to CPO mill's IRR of 40.9 and 41.7% respectively (see Figure 4-7). Under private investor funding, CPO mill's IRRs of 24.1 and 2.1% were noted for scenario 1 and 2 respectively (shown in Figure 4-7). The above suggests that, although the solid residue conversion to energy processes (as modelled) are not viable from a stand-alone perspective (as in the private investor financing), the processes (scenario 1 and 2) are economically viable under an integrated energy and CPO process perspective (as in the perspective of the CPO mill operator financing).

Daniel *et al*. (2014) indicated the high nominal interest rate of 24% on loans was the major contributing factor to the poor economic performances of bioenergy projects in Ghana, hence the analysis of alternative grants-funding schemes on the profitability of the process considered. The analysis considered scenarios of varying combinations of partial grant (at a discount rate of 0%) and the remaining investment cost funded by equity from private investor (at a discount rate of 40%). Thus, the magnitude of grant contribution to the investment cost affects the weighted average discount rate and subsequently the NPV of the processes. The results of the analysis (summarised in Figure 4-8) revealed both scenarios 1 and 2 are not economically viable even at 100% grant funding for the power price of $0.207/kWh.

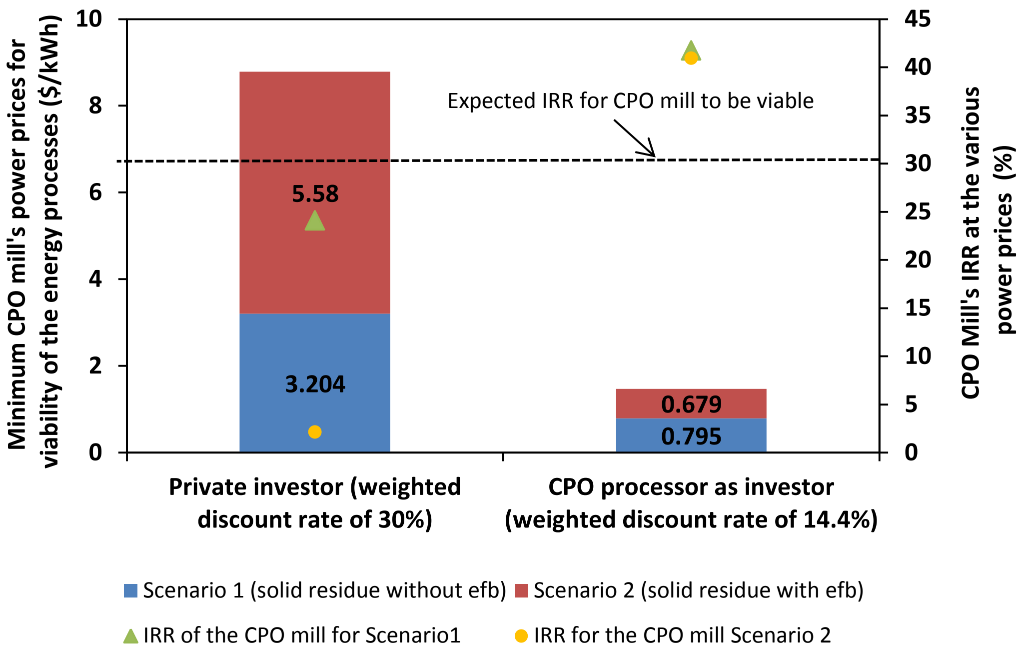


Figure 4-7: Minimum expected crude palm oil (CPO) mill's power prices (under assumption of all surplus generated power sold at prevailing grid price of $0.348/kWh), for private investor/CPO mill investor financings, and their corresponding impacts on the CPO mill's Internal Rate of Returns

On the other hand, at the power price of $0.348/kWh, scenarios 1 and 2 attained NPVs of $2.145 million and $1.774 million at 80% grant (remaining 20% by equity) and 65% grants (remaining 35% by equity) contributions respectively (Figure 4-8), thus suggesting their viabilities at or above the referred grant contributions. These findings also corroborate with the suggestion of high interest rate being the major impeding factor for feasibility of bioenergy projects in Ghana (Daniel *et al.*, 2014).

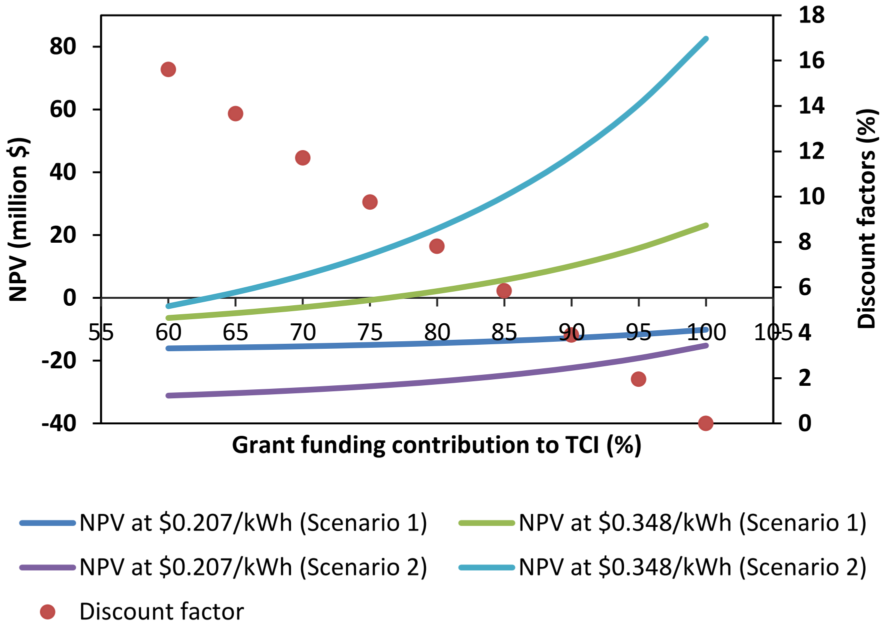


Figure 4-8: Variations in Net Present Value to changes in grant-equity financing schemes for the conversion of crude palm oil mill's solid residues to in-house energy process models

4.3.2 Technical and Economic Performances of the Anaerobic Digestion of Palm Oil Mill's Effluent to In-house Energy Process models

4.3.2.1 *Technical Performance of the Anaerobic Digestion of Palm Oil Mill's Effluent to In-house Energy Process models*

Table 4-11 summarises the result of the technical performances of the POME to in-house energy processes. From the result (Table 4-11), the gas-engine route attained 96.2% hot-water, 5.7% steam and 100% electric power requirement of the 13 ton FFB/hr CPO mill, while the steam turbine route attained only 28.7% steam and 22.3% of electric power demands by the CPO mill. Thus the results suggest a trade-off between thermal energies (80^{o}C hot water and 4 bar steam) and electricity depending on the CHP technology option with the steam-turbine favouring steam generation while the gas-engine favours power generation.

Table 4-11: Estimated technical performance of the anaerobic digestion of Palm Oil Mill Effluent to in-house energy process models

Rate of generation	Gas-engine route	Steam turbine route
Biogas[1]	2073	2073
Net power generation rate[2]	370	49
CPO Process steam[1]	2308 (5.65)[4]	11743 (28.72)[4]
CPO Process hot water[1]	29880 (96.16)[4]	-
CPO process electricity[2]	221(100)[4]	49 (22.29)[4]
Export electricity[2]	149	-
Technical performance		
Overall CHP efficiency (%)[3]	58.0	75.6

[1]expressed in tonnes per year; [2]given in kW; [3]The cleaning of the biogas was considered an integral operation of the CHP process. Hence the net electric power was determined as the gross power minus the sum of CHP process power demand and biogas cleaning process power demand; [4]Values in parenthesis represent percentage of actual energy demand by the 13 ton FFB/hr CPO mill attained.

Nevertheless, from the overall CHP efficiency as shown in Table 4-11, the steam-turbine route's 75.6% outperformed the gas-engine route's 58%. This can be attributed to the inability of recovering over 30% of the thermal energy from the gas-engine's exhaust streams as compared to the 85% efficiency of the steam boiler in the steam turbine route (see details in Appendix A3-A4). Furthermore, the high thermal energy in the prevalent steam at 4 bars and 215.7^{o}C in the steam turbine route as compared to the low thermal energy content of the dominant hot water (80^{o}C) in the case of the gas-engine route also contributed to the above noted CHP efficiencies (see Table 4-11).

4.3.2.2 *Economic Performance of the Anaerobic Digestion of Palm Oil Mill's Effluent to In-house Energy Process Models*

Capital Investment of the Anaerobic Digestion of Palm Oil Mill's Effluent to In-house Energy Process Models

Figure 4-9 presents the Total Capital Investment (TCI) and the Specific Capital Investment (SCI) for the POME to in-house energy processes. TCI of $5.492 million and $7.843 million were noted for the gas-engine and steam-turbine processes respectively (Figure 4-9). Additionally, SCI of $9340.79/kW and $48780.66/kW were noted for the gas-engine and steam-turbine processes respectively (see Figure 4-9). Yeoh (2004) obtained an SCI of $4178/kW (adjusted to 2014 value) for a 250 kW POME-biogas gas-engine power facility. Thus, the estimated SCI of $9340.79/kW for the 588 kW POME-biogas gas-engine CHP facility in this study can be noted to be higher by 55.3% when compared to the SCI of referred study, which could be attributed to the additional thermal generation components in the CHP scheme for this study as opposed to only power generation in the referred study.

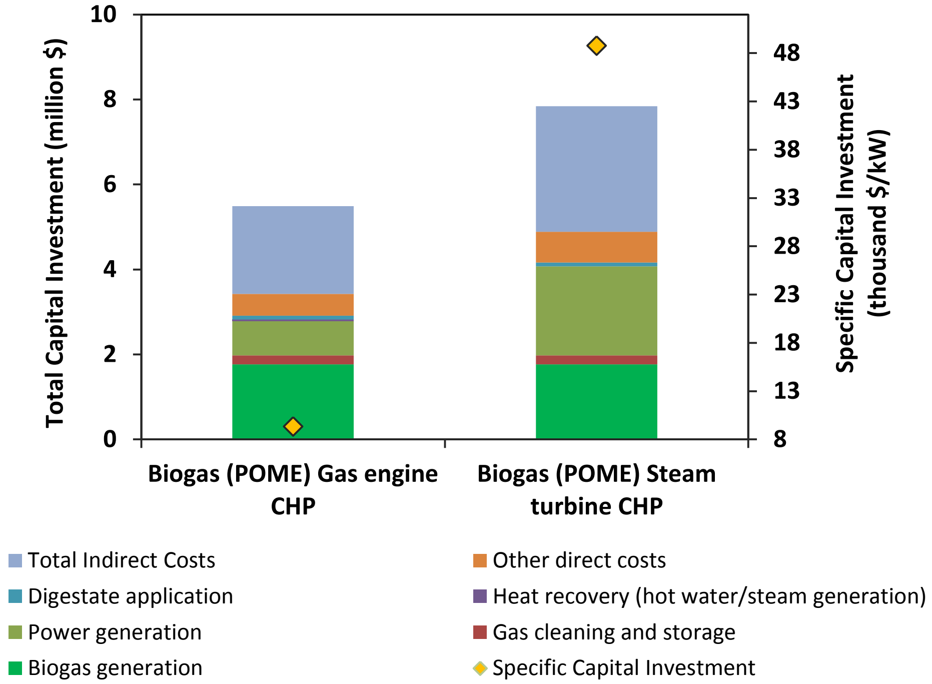


Figure 4-9: Breakdown of Total Capital Investment for anaerobic digestion of Palm Oil Mill Effluent to in-house energy models

Concentrating on only the CHP section of the facility, an estimated installed CHP cost of \$1803.76/kW (estimated from the results presented in Figure 4-9) for the gas-engine approach compares fairly to suggested installed CHP costs of \$463-1183/kW (adjusted 2014 value) (US EPA, 2014). On the other hand, the estimated installed CHP costs of \$14373/kW (estimated from the results presented in Figure 4-9) for the steam turbine route was noted to be too high when compared to suggested installed CHP cost of \$1100-2200/kW (adjusted to 2014 value) (US EPA, 2014). However, boiler steam turbine CHP technologies are one of the most sensitive power technologies to economies of scale as well as process conditions (IRENA, 2004), which could be the reason for the high difference in the referred technology's CHP cost above. Furthermore, the biogas generation section contributed 32.12 and 22.5% of the TCI for the gas engine and steam turbine processes respectively (shown in Figure 4-9). On the other hand, the power generation section accounted for 14.8% and 26.8% of the TCI for the gas engine and steam turbine processes respectively (see Figure 4-9). On the basis of installed equipment cost, the power generation section accounted for 27.8% and 50.5% of the installed equipment cost (estimated from the results in Figure 4-9) for the gas engine and steam turbine respectively, indicating the expensive nature of the power generation technology (boiler and steam turbine) at the relatively small capacity of 151 kW for the steam turbine process.

Operating Costs of the Anaerobic Digestion of Palm Oil Mill's Effluent to In-house Energy Process Models

The Total Operating Cost (TOC) and Specific Operating Costs (SOC) for the POME to in-house energy processes are given in Figure 4-10. The estimated annual TOC for the gas-engine and steam turbine CHP processes were $277000 and $319000 respectively (shown in Figure 4-10). Also, the SOC of $0.065/kWh and $0.276/kWh for the gas engine and steam turbine processes respectively (give in Figure 4-10) indicate attainment of significant decrease in cost of operation by 76.3% in the gas-engine process as compared to the steam turbine process. This could be due to the high operating labour and maintenance costs in the steam-turbine process (see Figure 4-10) although its power capacity was lower (see Table 4-11). The annual operating labour and maintenance cost of $185000 and $223000 for the gas-engine and steam-turbine processes respectively (shown in Figure 4-10) translates to specific operating labour and maintenance cost of $314.88/kW and $1384.91/kW respectively. This suggests a high decrease of 77.2% in the labour and maintenance cost for the gas engine process when compared to that of the steam turbine process. Thus the high labour and maintenance cost of the steam turbine technology cannot be justified by its low power output.

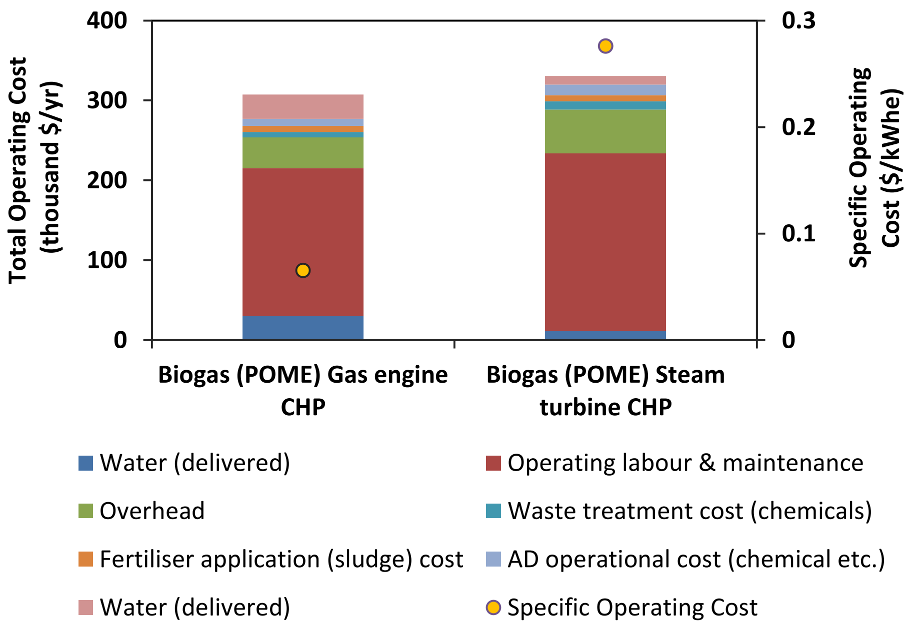


Figure 4-10: Total and Specific Operating Costs for the anaerobic digestion of Palm Oil Mill's Effluent to in-house energy Process models

4.3.2.3 *Profitability Assessment of the Anaerobic Digestion of Palm Oil Mill Effluent to In-house Energy Process Models*

The results of the economic assessment for the POME to in-house energy processes under the private investor financing (nominal discount rate of 30%) are summarised in Table 4-12. The results (given in Table 4-12) revealed at the grid electric power prices of $0.2073/kWh and $0.348/kWh, both the gas engine and steam turbine approaches could not attain the expected IRR of 30%. Also, of the two approaches investigated, the gas engine route was the most promising option with an IRR of 14.9% and a pay-back period of 9 years at the power price of $0.348/kWh (as shown in Table 4-12). Yeoh (2004) suggested payback periods between 5 to 7 years are appreciable for such bioelectricity facilities. From a sensitivity assessment, eliminating the income taxes of 25% reduced the gas-engine route's payback period to 7.5 years suggesting governmental interventions such as tax free incentives can contribute to the sufficing of the gas-engine approach. Under conditions of selling the generated power at the grid power prices, the gas engine and steam-turbine approaches attained negative NPVs ranging between -$4.7 and -$14.5 million (see Table 4-12). This suggests all the considered approaches incur losses over the capital investment (equivalent to the positive magnitudes of their NPVs) under the economic assumptions of private investor and grid power conditions. Therefore from an NPV point of view, the processes still remain economically unviable.

Table 4-12: Private investor financing results for the anaerobic digestion of Palm Oil Mill Effluent to in-house energy process models

Parameters	Electricity s.p. of $0.207/kWh		Electricity s.p. of $0.348/kWh	
	Gas-engine	Steam turbine	Gas-engine	Steam turbine
NPV (million $)	-6.39	-14.47	-4.71	-14.22
IRR (%)	7.8	-0.8	14.9	0.2
Payback period (yrs)	11.3	14.3	9	13.7

Additionally, sensitivity assessment revealed bioelectricity price of $0.753/kWh and $9.403/kWh for the gas-engine and steam-turbine routes (respectively) were required to attain the expected IRR of 30%, which translate to 53.8% and 96.3% (respectively) higher than the present maximum power price of $0.348/kWh. The referred increments are higher than suggested justifiable increment of 20% over fossil based power prices to account for environmental contributions of renewable power (Leibbrandt, 2010).

The outcomes of the profitability assessment for the AD of POME to CPO mill's process energies under the operator of the CPO mill as investor financing scheme [60% loan (at 24% interest rate) and 40% equity (at 0% interest rate), having a weighted discount rate of 14.4%] is presented in Table 4-13. The results (presented in Table 4-13) indicate no significant variations in the NPVs and IRRs when compared to the NPVs and IRRs of the private investor financing scheme (at 30% discount rate) (see Table 4-12). However, the gas-engine route attained IRRs of 7.8 and 14.9% at the prevailing power prices of $0.207/kWh and $0.308/kWh respectively, suggesting the process is economically viable at the maximum power price of $0.308/kWh when the expected IRR of 14.4% is taken into consideration.

Table 4-13: The operator of the CPO mill (as investor) financing structure's results for the anaerobic digestion of Palm Oil Mill Effluent to in-house energy process models

Parameters	Electricity s.p. of $0.207/kWh		Electricity s.p. of $0.348/kWh	
	Gas-engine	Steam turbine	Gas-engine	Steam turbine
NPV (million $)	-3.70	-12.90	0.31	-12.34
IRR (%)	7.8	-0.8	14.9	0.2
Payback period (yrs)	11.3	14.3	9	13.7

Figure 4-11 highlights the impacts of the minimum expected CPO mill's power prices for the private investor/operator of the CPO mill investor financings on the profitability of the CPO process [under an assumption of the steam turbine approach meeting all the CPO mill's power demands]. The results (given in Figure 4-11) revealed the gas-engine route's expected minimum power prices for the private investor ($0.753/kWh) and the operator of the CPO mill as the investor ($0.337/kWh) result in the CPO mill attaining IRRs of 41.2 and 44.1% respectively. These IRRs exceed the expected CPO mill's IRR of 30%, thus the gas engine route can be said to be viable under both private investor or the operator of the CPO mill as the investor conditions (i.e. under conditions of a stand-alone facility or an integrated energy/CPO process point of view). Also, the steam turbine route's minimum expected prices for the private investor ($9.403/kWh) and operator of the CPO mill financings ($3.59/kWh) resulted in IRRs of 0 and 21.2% respectively, suggesting the steam turbine process is not viable considering the expected IRR of 30% for the CPO process (see Figure 4-11). Therefore, based on the outlook of the profitability of the CPO milling process, the gas-engine approach can be said to be viable under both private investor (discount rate of 30%) and operator of the CPO mill as investor (discount rate of 14.4%) financing terms.

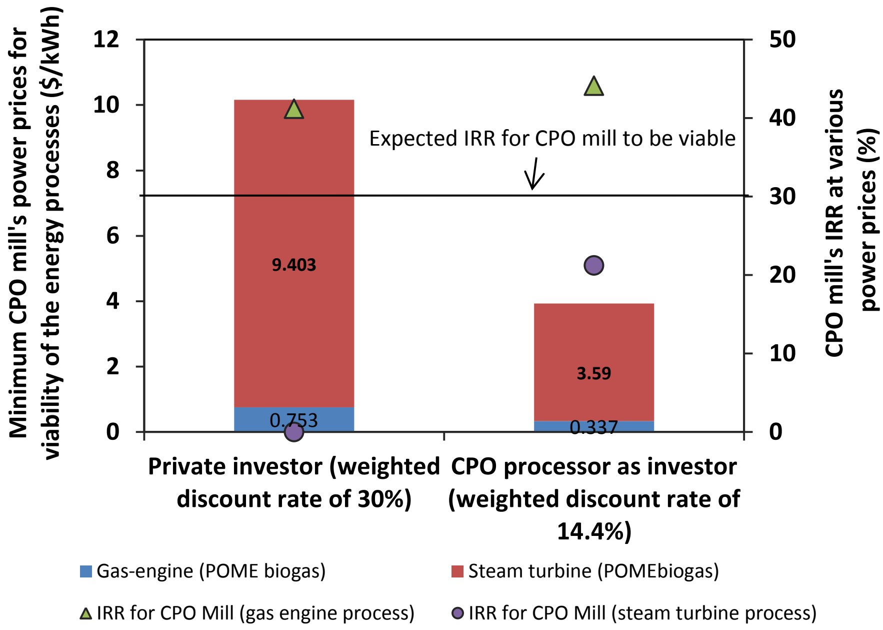


Figure 4-11: Minimum expected crude palm oil (CPO) mill's power prices [under assumption of the steam turbine approach meeting all the CPO mill's power demands], for private investor/CPO mill investor financings, and their corresponding impacts on the CPO mill's Internal Rate of Return

The economic assessment of various combinations of grant and equity financing schemes [part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)] on the profitability of the POME biogas energy processes is given in Figure 4-12. At the prevailing grid power price of $0.207/kWh, it was realised that the steam turbine route attained an NPV of $576000 for grant funding of 90% and 10% equity, while the gas-engine route achieved an NPV of $234000 at 60 and 40% grant and equity funding respectively (see Figure 4-12). Similarly, at the base power price of $0.348/kWh, the gas-engine approach attained an NPV of $158000 under a funding scheme of 40% grant and 60% equity, whereas the steam turbine process gained an NPV of $1.834 million at 90% grant and 10% equity funding. Thus, suggesting the gas-engine and steam-turbine approaches are economically viable under grant-equity funding.

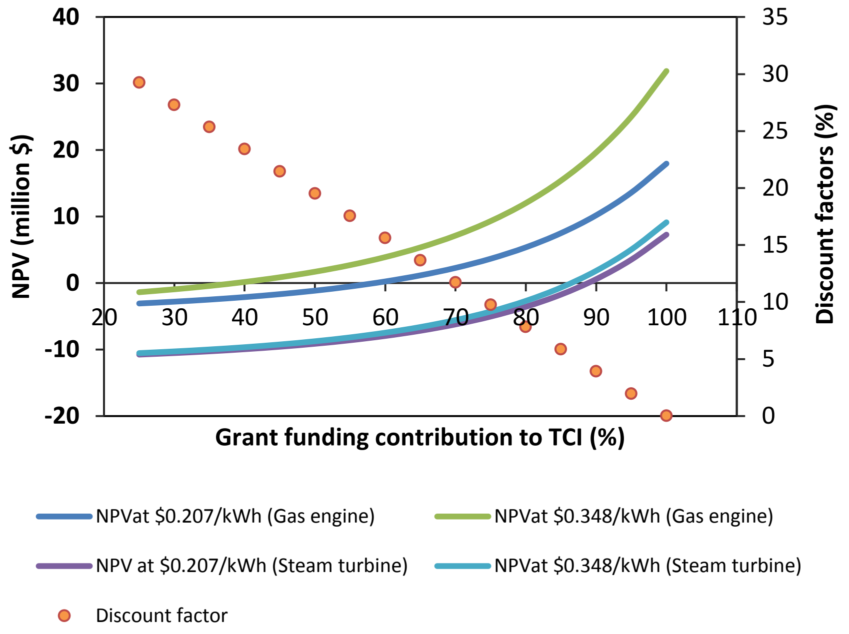


Figure 4-12: Variations in Net Present Value to changes in grant-equity financing schemes for the anaerobic digestion of Palm Oil Mill Effluent to in-house energy process models

4.4 Conclusions

The study showed that the generated solid bio-residues (efb, mf, pks) in a CPO mill of 13 tons FFB/hr capacity could meet the mill's in-house energy requirement (40885 tons steam/year, 31075 tons hot water/year and 221 kW electricity), as well as generate surplus electricity of 630 kW (scenario 1, efb excluded) and 2280 kW (scenario 2, efb added), via means of a steam turbine CHP technology. On the other hand, anaerobic digestion (AD) of the palm oil mill effluent (POME) could not generate enough biogas to meet the in-house energy demands, by means of a gas-engine or steam turbine CHP technologies. The gas-engine route could meet 96.2% hot-water, 5.7% steam and 100% electrical power demands of the mill, while the steam turbine route attained only 28.3% of steam and 22.3% of electric power demands.

Although the solid residues on their own could meet the in-house energy demands and generate surplus electricity for export purposes, integrating the POME biogas and the solid residues as boiler fuel in a steam turbine CHP scheme could maximise the surplus electricity. In addition, the sensitive nature of steam turbine CHP technologies to economies of scale (IRENA, 2012a) suggests integration of solid residues and biogas as the boiler fuel could be financially rewarding as the capacity of power generation would be increased, and thus worthy of consideration in converting the available CPO mills bio-residues for the purpose of export power generation.

The economic models showed that bioenergy generation from the CPO mill bio-residues for in-house energy purposes is generally expensive as compared to the grid power. This was mainly due to high interest rates of 24% on bank loans, as grant financing [part grant (at discount rate of 0%) and remaining investment cost from equity (at discount rate of 40%)] resulted in the in-house bioenergy processes to become viable at the prevailing grid power prices. Nonetheless, under conditions of the operator of the CPO mill as the investor [60% loan (at 24% discount rate) and 40% equity by the operator of mill (at 0% discount rate)], the expected power prices for scenario 1 ($0.795/kWh), scenario 2 ($0.679/kWh), and the POME-biogas gas-engine ($0.337/kWh) approaches resulted in profitability of the CPO milling process with attainment of IRRs ranging 40.9-44.1% (for an expected IRR of 30%). Considering the difficulty in accessing national grid power for running the mills, the implementation of in-house bioenergy generation by the operator of the CPO mill is encouraged as it assures energy security for the CPO facility, as well as results in profitability of the CPO milling process.

Integration of bioenergy cogeneration from biomass residues in CPO processing is possible. The bioenergy cogeneration advances CPO processes to realise economic viability. Additionally, surplus power from the cogeneration process provides solution to the lack of electricity that restricts socio-economic development in Africa, and therefore such bioenergy scenarios provide an avenue for advancing socio-economic development, particularly in the underdeveloped rural areas.

5 FEASIBILITY ASSESSMENT OF CONVERSION OF IN-HOUSE SOLID RESIDUES FOR PROCESS ENERGY PRODUCTION IN CASSAVA FLOUR MILLS

Summary

The potential and economic viability of in-house electricity and dryer heat energy generation in a semi-mechanised (4.8 tons cassava/day) and mechanised (10 tons cassava/day) cassava flour (CF) mills, utilising the peels residues as energy source, was assessed. Process and economic models were developed with Aspen Plus® simulation software and Microsoft Excel respectively, employing technical data from literature and the 2014 economic context of Ghana.

The identified major energy forms of the semi-mechanised and mechanised CF facilities were electricity and diesel (as dryer fuel). Thus gasification and anaerobic digestion (AD) were considered as potential energy conversion pathways, for in-house energy generation from the available residues. In both conversion pathways, available literature suggested supplementing the peels with external biomass resources was required to make the processes feasible. Hence, cattle dung and wood shavings/sawdust as feedstock supplements in the AD and gasification paths respectively were considered.

The process models revealed both the AD and gasification scenarios (as modelled) could realise the dryer energy and power demands of the mills (0.5 kW and 14.47 kW for the semi-mechanised and mechanised CF mills respectively), in addition to generating surplus power of 91.5 kW (semi-mechanised CF) and 194.53 kW (mechanised CF) for the AD approaches, and 14.67 kW (semi-mechanised CF) and 32.7 kW (mechanised CF) for the gasification approaches.

The economic models showed that, under private investor financing [60% loan (at an interest rate of 24%) and 40% equity (at an assumed interest rate of 40%), weighted nominal discount rate of 30%], the AD approach was the most promising with expected power prices of \$0.426-0.602/kWh (which have the same order of magnitude as grid power prices of \$0.207-0.348/kWh), while the gasification approach's expected power prices of \$1.573/kWh (semi-mechanised CF capacity) and \$0.653/kWh (mechanised CF capacity)

suggests its viability is dependent on the capacity. However, under grant-equity financing [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)], the AD processes and mechanised CF mill's gasification processes were economically viable at 40-70% grant contributions (remaining 60-30% financing by equity) and 50-95% grant contributions (remaining 50-5% financing by equity) respectively. Thus, the high interest rate on loans is a major contributing factor to the economic viability of the processes. Nonetheless, under financing by the CF mill operator [60% loan (at 24% interest rate) and 40% equity from the operator (at 0% interest rate), weighted nominal discount rate of 14.4%] with a view of securing energy for the CF process, the CF mill's process power could be supplied by the AD processes at no cost if the surplus power could be sold at the maximum grid price of $0.348/kWh. This financing outline results in the CF mills achieving IRRs between 42.8-96.3% (compared to an expected IRR of 30%), and hence the most promising financing approach of implementing the bioenergy integration in the CF mills.

5.1 Introduction

Cassava flour (CF) production in Africa is receiving much attention as an economically valuable product, with the emergence of its global uses in food applications such as baking flour, soup thickeners and non-food applications such as glue binders and starch in textile industries (Nweke, 2009; Nang'ayo *et al.*, 2005; Dziedzoave *et al.*, 2003). Demonstrations revealed it was technically feasible to produce high quality CF at an industrial scale employing existing mechanised units (Kleih *et al.*, 2013; Dziedzoave *et al.*, 2003). However, production of CF in the cassava growing belts in SSA is still predominantly limited to small-scale or cottage facilities, which are characterised by low production capacities and poor product quality, thus failing to meet the growing market demands (Nyirenda *et al.*, 2011; Nang'ayo *et al.*, 2005; Kleih *et al.*, 2013). The shortage of supply and high cost of electricity and fossil fuels, required to drive the mechanised industrial units, have been cited as one major factor for the minimal implementation of the industrial CF milling facilities (Kleih *et al.*, 2013; Serpagli *et al.*, 2010a).

In addressing the energy concerns of the industrial mechanised CF facilities, attention has been given to converting the generated solid biomass residue to the CF mill's in-house energy (Serpagli *et al.*, 2010a; 2010b). Reported solid biomass residues in cassava processing include discarded roots, peels and bark, which are often collectively called peels (Serpagli *et al.*, 2010a). It is estimated that peels comprise about 10-13% of the fresh roots and the barks are about 6-7% of the weight of the tuber (Serpagli *et al.*, 2010a). Likewise, estimations indicate about 13.6% of the mass of the edible tuber is often lost to the peels during manual peeling (Kreamer, 1986). In most cases, small quantities of the referred wastes, usually peels and discarded tubers are fed to ruminants. The greater remaining portions are often abandoned near processing sites, used as landfill or burnt which consequently contributes to environmental pollution (Serpagli *et al.*, 2010a).

For the purposes of utilising the solid residues for in-house energy generation, the appropriate biomass-to-energy conversion technology choices must take into consideration the amount of solid residues generated, the physical properties of the residues and the end use energy forms required (McKendry, 2002). The estimated energy-mix in the semi-mechanised and mechanised cassava flour processes under study (see Figure 3-23, section 3.3.2) indicates electricity and diesel (as dryer fuel) as the major forms of energy required. Furthermore, the physical properties of cassava peels have been noted to be suitable for gasification and anaerobic digestion (AD) to syngas and biogas respectively, which could be utilised as dryer fuel or generating electricity (Serpagli *et al*., 2010a; 2010b).

The purpose of this study was to investigate the financial feasibility of gasification and AD routes for conversion of generated cassava peel residues to in-house process energy for a semi-mechanised (4.8 tons cassava/day) and mechanised (10 tons cassava/day) CF mill in the African context. This was achieved through developing process and economic models for conversion of the biomass residues to in-house energy generation. Experimental data, process and economic parameters from literature were considered in developing the models. Conservative assumptions, based on the African context were made in instances where literature was not available. The results allowed for comparing the gasification and AD routes to determine the most feasible approach for converting the CF mill's solid residues to the process energy.

5.1.1 Limitations and Interventions for the Gasification and Anaerobic Digestion Routes of Converting Cassava Peels to Cassava Flour Mill's Process Energy

5.1.1.1 *Concerns and Intervention in the Anaerobic Digestion of Cassava Peels to Cassava Flour Mill's Process energy*

In SSA, several aspects of small-scale biogas technologies for rural applications particularly in household cooking, have been explored in the past decades (Tumwseige *et al*., 2012). Promoting factors of AD implementation in the rural areas were availability of feedstock, commonly animal dung, and the simplicity of the AD technology (Karekezi, 2002). According to Karekezi and Kithyoma (2003), several demonstrations and field tests revealed AD technology was technically viable in African rural settings. However, mass deployments were not successful due to unforeseen challenges in feedstock security. It was observed that small-scale animal farmers had challenges of securing sufficient feedstock to ensure steady generation of the biogas (Karekezi, 2002). Also, the investment cost of even the smallest biogas units proved to be a challenge for most poor rural households (Karekezi and Kithyoma, 2003).

AD processes are highly dependent on the type of feedstock and differ according to the feedstock's dry matter content. Feedstocks with dry matter contents of 20-35% (e.g. agro residues, municipal solid waste and energy crops) and wet organic wastes with dry matter below 20% (e.g. animal farm manure and food waste slurries) are suitable for applications in the so called dry and wet digestions respectively (Al Seadi *et al.*, 2008). In the dry digestion, commonly a batch process, the feedstock is stacked in the digester without the addition of water (BioFerm, 2009). Wet digestion on the other hand involves feedstock that can be pumped into the digester. The referred feedstocks for dry-digestion are also applicable in the wet digestion but require conditioning by crushing and addition of water (Mata-Alvarez, 2002). A general comparison between dry and wet AD processes, shows dry digestion has higher biogas yield per unit volume of digester and vice-versa for biogas yield per unit of feedstock (Angelonidi and Smith, 2014; Jha, 2012). In terms of energy requirements, lower energy demands for heating purposes in the dry digestion due to less water fraction stands as an advantage over the wet digestion (Jha, 2012). Dry digestion also requires longer retention times and additional equipment for mixing and transport of feedstock as compared to the wet process. A study on AD of municipal solid waste and food waste in Europe (Angelonidi and Smith, 2014) also showed specific capital investments ($/m^3 biogas and $/tonne of waste) to be higher for the dry digestion process, as compared to the wet digestion. Both wet and dry AD processes have reached industrial applications (Angelonidi and Smith, 2014).

In view of the proven applications of AD technology, this technology can potentially be applied for cassava peels residues to biogas conversion (moisture content of about 65 wt% - Ukwuru and Egbonu, 2013). However, low biogas yields (0.6 l/kg-TS at thermophilic conditions and retention period of 30 days) from AD of cassava peels due to its high carbon-nitrogen ratio (C/N ratio of 48.7) and thus high recalcitrance to biological degradation in the AD process have been reported (Adelekan, 2012). This has been attributed to the faster consumption of available nitrogen by methanogenic bacteria for meeting their protein requirements, after which they become inactive and no longer react with the excess carbon in the substrate, to produce the methane component of biogas (Karki *et al.*, 1994). Table 5-1 shows typical chemical compositions of undigested and digested cassava peels with high C/N ratios of 48.7 and 46.7, respectively, depicting its low reactivity in the AD process. Ideal C/N ratios of some suitable AD feedstocks such as human excreta, pig dung, sheep dung, and cow dung are 8, 18, 24 and 19, respectively (Karki and Dixit, 1984).

Adelekan (2012) suggested mixing the cassava peels with a much lower C/N material such as animal dung, could stabilize the mixtures' C/N ratio to values between 22 and 30, and thus improving the digestibility for biogas generation. It has been shown that higher biogas yields of 21.3, 35.0 and 13.7 l/kg TS could be achieved for mixtures of cassava peels with cattle, piggery and poultry dungs, respectively, in mixing ratios of 1:1 for a retention period of 30 days (Adelekan, 2012).

Table 5-1: Elemental composition of cassava peels

Parameters	Undigested peels	Digested peels
Organic Carbon[1]	48.7	46.4
Total Nitrogen[1]	1.0	1.0
C/N ratio	48.7	46.4
K[1]	1.1	0.7
P[1]	1.6	0.8
NO_3[1]	0.16	0.12
Zn[2]	125	118
Cu[2]	15	12
Mn[2]	180	172

[1]expressed as percentage; [2]expressed as mg per kg peels.
Source: Adelekan and Bamgboye, 2009

Application of Digestate from Anaerobic Digestion of Cassava Peels as Biofertiliser

Application of chemical fertilisers has been associated with environmental degradation through eutrophication (due to run off or leachate into water tables), poor soil quality in the long run (due to constant loss of humus and micronutrients), and heavy metal pollution (Zhu *et al.*, 2012; Holm-Nielsen *et al.*, 2009). Digestate, a nutrient rich by-product of the AD process, has been a promising alternative to chemical fertilisers with benefits such as slow decomposition rate, thus being suitable for nutrient uptake and assimilation in plants, and lowering leachate risk among others (Möller *et al.*, 2009). Furthermore, a study suggests the average nutrients content in digestate (bioslurry) is significantly higher than in farm yard manure or composted manure (SNV, 2011). However, the presence of harmful microbes in digestate poses health risk to its end users and consequently limits its potential in direct biofertiliser applications, and which may require treatment (e.g. pasteurisation) to address these risks (Alfa *et al.*, 2014).

Little is known about the safety and treatment conditions required for the digestate from the AD of cattle dung/cassava peel for end use as biofertiliser. In a related study on co-digestion of human excreta and household food waste, it was observed that though beneficial nitrogen fixing (*klebsiella* and *Clostridium spp*) and phosphate solubilizing (*Bacillus* and *Pseudomonas spp*) microbes were in the digestate, the presence of some harmful microbes such as salmonella and residual levels of total coliform bacteria of 2.10 $x10^{\wedge 8}$ CFU/100ml, were unsafe for direct application as biofertiliser (Owamah *et al.*, 2014). The authors recommended that longer substrate retention time of 90 and 30 days for mesophilic (30-42 ^{o}C) and thermophilic (43-55 ^{o}C) AD processes, respectively, to ensure that biofertiliser digestate of acceptable quality could be obtained.

5.1.1.2 *Concerns and Intervention in the Gasification of Cassava Peels to Cassava Flour Mill's Process Energy*

Gasification is a thermo-chemical process involving partial thermal oxidation of solid carbonaceous materials into combustible syngas (CO_2, water, carbon monoxide, hydrogen and gaseous hydrocarbons), which is often utilised in electric power generation via gas engines or gas turbines, and having solid char, ash and condensable compounds (tars and oils) as minor by products (Puig-Arnavat *et al*., 2010). According to François *et al.* (2012), CHP plants that employ biomass gasification have received considerable attention in recent years, due to advancement in syngas cleaning technologies and the potential high electrical efficiency of about 25%, when compared to conventional combustion units – thus addressing the iomass gasification challenges attributed to the damaging effect of the tars and inorganic components of the produced syngas on downstream equipment.

The proximate analysis and physical properties of dried cassava peels at 20% moisture (shown in Table 5-2) show this material to be appropriate for gasification (Serpagli *et al*., 2010a). However, estimations by Serpagli *et al.* (2010a; 2010b) revealed the quantity of peels residues generated by maximum CF mill capacity of 10 tons cassava/hr (present study) were insufficient to meet the thermal and electrical energy demands of the mill and the peels feedstock drying. The application of biomass gasification is further limited by the available installed capacities of 5-2200 KW. Thus, implementation of gasification in the available installation capacities will require additional biomass resources to supplement the available cassava peels.

The prevalent smallholding farm and small agro-processing facilities in SSA produces minimal quantities of dispersed biomass wastes, which makes mobilisation of these agro-process waste for bioenergy expensive and often impractical (Belward *et al*., 2011). On the other hand, wood shavings and sawdust are ideal as supplementary feedstocks for the gasification of peels to power, considering they are common and available in high volumes at sawmills and wood processing sites (Duku *et al*., 2011)

Table 5-2: Proximate and physical properties of cassava peels

Parameters	Dried Sample	Wet Sample
Ash[1]	3.4	4.9
Volatile[1]	78.3	95.1
Fixed carbon[1]	18.3	
Bulk density[2]	286	340
Moisture[3]	2.2	66.2
Ignition test	Burns easily	NA
Flow ability test	Flows easily	NA

[1]expressed in % dry weight; [2]expressed in kg/m^3; [3]given in % (w/w); N.B: For ash fusion test, no ash fusion at 1200^{o}C for the dried and wet samples.
Source: Serpagli *et al.*, 2010a

Wood shavings and sawdust by themselves are not well-suited for gasification, mainly due to the low bulk density when mixed (as shown in Table 5-3) and poor flow characteristics for feeding into the gasifier, both of which will reduce the gasification efficiency. However, a blend of wood shavings/sawdust (in 7:3 proportion) and dried cassava peels in a 1:1 proportion improved the flow ability in the gasifier and consequently the efficiency of the process (Serpagli *et al.*, 2010b). Thus, a win-win situation when the referred residue combination is employed in the gasification to in-house energy for the cassava flour mill.

Table 5-3: Proximate and physical properties of mixture of wood shavings and sawdust (in 7:3 proportions)

Parameters	Naturally Dried Sample	Wet Sample
Moisture (%)	19.83	30.60
Ash (% of dry wt)	1.29	2.33
Volatile (% of dry wt)	78.59	97.66
Fixed carbon (% of dry wt)	20.12	
Bulk density (kg/m^3)	68	95
Ash fusion test	No ash fusion at 1200 ^{o}C	No ash fusion at 1200 ^{o}C
Shape and size	Irregular shape	Irregular shape
Ignition test	Burns easily	NA
Flow ability test	Does not flow easily	NA

Source: Serpagli *et al.*, 2010a

5.2 Methodology

5.2.1 Developing Conceptual Configurations for the Gasification and Anaerobic Digestion of Cassava Peels to Cassava Flour Mill's Energy Process Models

Considering the electric power demands of the semi-mechanised and mechanised CF mills ranged between 0.45-14.47 kW, which were minimal for power technologies, their anaerobic digestion (AD) and gasification routes to in-house energy processes' capacities were based on the available peels (residues) generated by the study's adopted semi-mechanised (1317 kg peels /day) and mechanised (2971 kg peels/day) CF mills (see Figure 3-10, Figure 3-12 and Figure 3-14 in subsection 3.3). Excess power, if any, was to be sold as export power. For simplicity, the anaerobic digestion (AD) and gasification to in-house energy processes corresponding to the semi-mechanised and mechanised CF mills are hereafter referred to as semi-mechanised CF and mechanised CF mill's AD or gasification energy facilities (respectively) in subsequent sections. Details on developing the configuration of the considered gasification and AD energy routes are presented in the subsections below.

5.2.1.1 *Configuration of the Anaerobic Digestion of Cassava peels to Cassava Flour mill's Energy Route*

As noted above in section 5.1.1.1, co-digestion of cassava peels and pig dung resulted in the highest biogas yield, followed by co-digestion with cattle dung (Adelekan, 2012). The production of pigs in SSA is expected to be lower than that of cattle, due to religious beliefs that exclude pigs from human consumption, following similar trends in Ghana where cattle production is estimated to be 2.7-fold higher than pig production (MoFA, 2013). Consequently, cattle dung might be the most accessible co-substrate and therefore the choice considered in this study. Production of cassava and the potential generation of its peels residues, which demonstrate reliability of the peels as AD feedstock in the context of SSA, have been shown in sections 2.1.1.3 and 3.3.4 respectively. Therefore, only the cattle dung as a co-substrate's demand is considered under this section. Studies estimate the average dung generation rate of a cow at 10-12 kg/day (Otim *et al.*, 2011; Larson and Kartha, 2000). Under the assumption of the least case of 10 kg/day, 132 and 298 cows (estimated as in Equation 16-17 below) are expected to suffice for the dung demands of the considered medium and large scale facilities respectively.

$$\text{Daily dung requirment} = \frac{\mathrm{M_{dung}}}{\mathrm{R_T}} \tag{16}$$

$$\text{Number of cows required} = \frac{\text{Daily dung requirement}}{\mathrm{M_{dcd}}} \tag{17}$$

Where: M_{dung} is the amount of cattle dung required per batch (kg/batch)

R_T is the retention period per batch (days/batch)

M_{dcd} is the amount of dung per cow per day (10kg cow^{-1} day^{-1})

Furthermore, considering the main forms of energy in the conventional CF processes are diesel (dryer fuel) and electricity, the bio-energy integration scenario considered fuelling the dryer with part of the generated biogas, while the remaining biogas is used for the electric power generation. The conceptual approach is summarised in the schematic diagram in Figure 5-1.

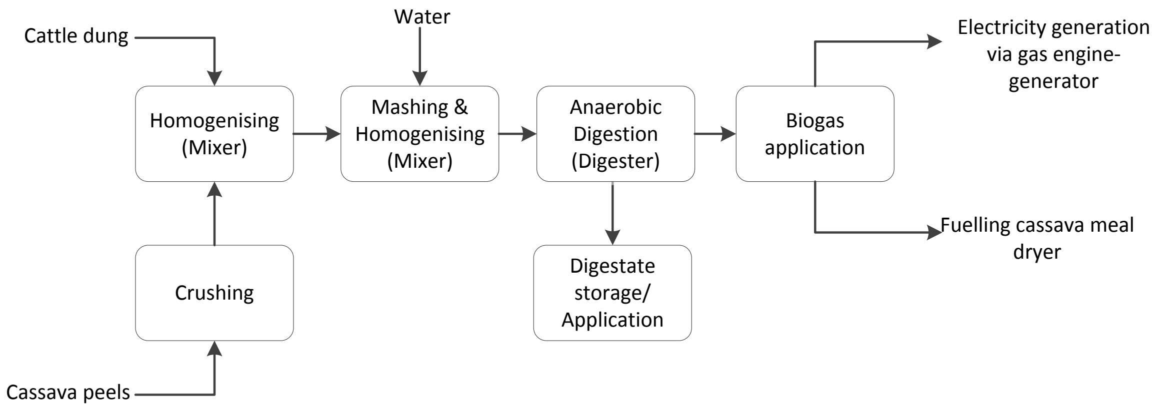


Figure 5-1: Block flow diagram for anaerobic digestion of cassava peels/cattle dung to cassava flour mill in-house energy process

5.2.1.2 *Configuration of the Gasification of Cassava Peels to Cassava Flour Mill's Process Energy Route*

The conceptual approach of the gasification route was adopted from the work of Serpagli *et al.* (2010b). The authors carried out experimental and techno-economic assessment of gasification of a blend of wood shavings/sawdust (in 7:3 proportion) and dried cassava peels in a 1:1 proportion for purposes of in-house energy in a CF mill under the Ghanaian year 2010 context. The result suggested the process was technically feasible thus the adoption of their feedstock mix and process conditions for this study. The process configuration considered in this study involved utilising portion of the syngas in power generation via gas-engine generator. The remaining portion of the generated syngas is then used as cassava grit/chip dryer fuel, while also augmenting the hot exhaust gases from the gas engine in drying of the feedstock, as shown in the schematic diagram in Figure 5-2.

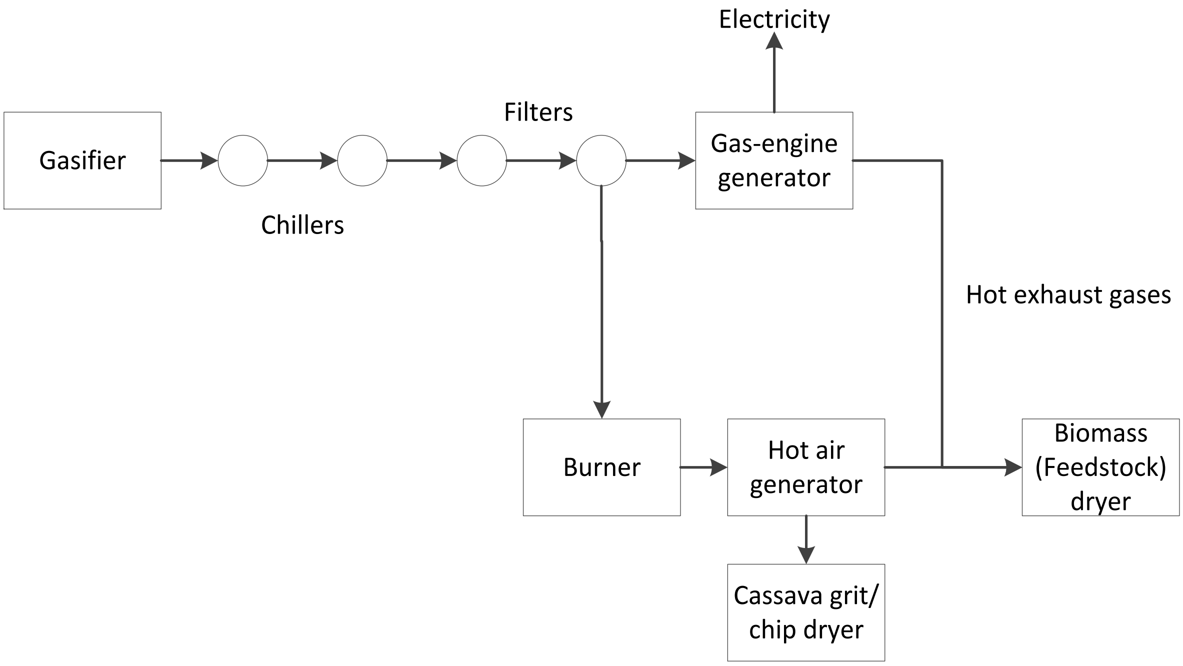


Figure 5-2: Block flow diagram of gasification of peels/wood shavings/sawdust to cassava flour mills in-house energy process (redrawn from Serpagli *et al.*, 2010b)

5.2.2 Conversion of Cassava Flour Mill's In–house Peels Residue to the Process Energy Process Modelling Basis and Approach

5.2.2.1 *Basis and Approach of the Anaerobic Digestion of the Cassava Peels/Cattle dung to Cassava Flour mill's Energy Process Modelling*

Specific literature on medium or large scale AD facilities for digestion of cassava peel/cattle dung (as in the cases of the semi and mechanised CF mill's AD facilities) was not available, thus the process modelling was based on common operational requirements and technical know-how from literature on similar AD processes, involving agricultural waste or dedicated energy crops and animal dungs. The selection of process equipment from available options was undertaken having in mind its economic and technical compatibility with the African rural settings. Furthermore, the biogas facility was modelled as a stand-alone with the primary objective of supplying the energy demands of the CF facility and exporting excess if any. An operational period of 300 days/yr was assumed for the process.

The process commences with mobilisation and transportation of feedstock (cassava peels and cattle dung) to the biogas facility, which was assumed to be in the vicinity of the cassava flour (CF) mill. The feedstock (cassava peels and cattle dung) was assumed to be obtained and transported to the biogas facility at a delivered cost of $10/ton (Serpagli *et al.,* 2010b). For ease of handling and improving the AD process efficiency, solid feedstock such as cassava peels required conditioning and homogenisation (in the case of co-digestion), to ensure stability of the AD process, as wide fluctuations in feed compositions stresses the AD microorganisms and reduces the biogas yield (Al Seade *et al*., 2008). In the pre-treatment of the feedstock to attain the required conditions, as reported by Adelekan (2012), the cassava peels were crushed into smaller particle sizes, mixed with equal weight of cattle dung and homogenised in a mixing tank. Mashing of the homogenised feedstock to ensure its ease of flow and right conditions for the AD process was then achieved by addition of an equal mass of water and homogenised in the same mixer, prior to feeding into the digester. In the process modelling, the AD-based process of peels to in-house energy was divided into the anaerobic digestion (AD), biogas cleaning/power generation and digestate pretreatment sections as described below.

Anaerobic Digestion (AD) of the Cassava Peels/Cattle dung Process Modelling

The adopted process conditions from Adelekan (2012) are summarised in Table 5-4. In the experimental procedure of the adopted study conditions, the digester was charged once with the batch feedstock for a retention period of 30 days. However, controlling the microbial conditions for an efficient AD process in medium or large scale facilities is a challenging task, which demanded additional equipment and energy, thus increasing the operational cost (Al Seade *et al*., 2008). Considering this and the adaptability of technology to the African rural settings, the VacVina rural digester model, which is technically proven in Asian rural areas with similar conditions to the African rural settings, was adopted in this study (CCRD/VACVINA, 2004). This type of rural AD reactor usually has fermentation chamber volumes of $100m^3$ and operated in batch-wise feeding mode (Samer, 2012). Hence, 3 and 6 such digesters (reactors) were assumed to be employed for the semi-mechanised and mechanised CF mill's AD facilities respectively (see details of the volumes of the reactors in Table 5-4). The ability of the VacVina digester to function as underground systems also helps to minimise land space requirements (CCRD/VACVINA, 2004). In its operation, new substrate is often added once daily, with an equal amount of digestate slurry displaced from the reactor. In order to be consistent with the adopted experimental conditions of Adelekan (2012) in this study, the sizing of the digester was based on an assumption of feeding once per batch (30 days retention period), after which the digester is then discharged for recharging with new batch of feedstock (Samer, 2012). The sizing of the digester was determined as shown in Equations 18-20 (Samer, 2012).

Table 5-4: Process and operational parameters for the cassava peels/cattle dung anaerobic digester (based on Adelekan, 2012)

Parameters	Parameters from Adelekan (2012)	Estimate for semi-mechanised CF AD facility	Estimate for mechanised CF AD facility
Design Basis			
Cassava peels (kg/batch)	5	39520[1]	89115[2]
Cattle dung (kg/batch)	5	39520	89115
Water (kg/batch)	10	79040	178230
Operating Parameters			
Total reactor volume (m^3)	-	243[3]	548[3]
Digester temperature (^oC)	32 – 40	32 – 40	32 – 40
Retention period (days/batch)	30	30	30
Biogas production rate (m^3/ batch)	2.13	57314[4]	129240[4]
Annual biogas (m^3/yr)	-	573140	1292400
Annual digestate (kg/yr)	-	537680	2388520

[1] Estimated as sum of solid residues (peels (831.73kg/day) + edible portions lost to peels (485.57kg/day)) accumulated for 30 days in a medium Cassava flour (CF) facility with a daily capacity of 4.807tons fresh cassava.
[2] Estimated as sum of solid residues (cassava peels (1730kg/day) + edible portions lost to peels (1240.5kg/day)) accumulated for 30days in a large scale CF facility with a capacity of 10tons fresh cassava/day.
[3] Determined as the sum of volumes of total substrate charged/batch and daily volume of biogas generated. Bulk densities of cassava peels and cattle dung used in their volume estimations are 340kg/m^3 (Serpagli et al., 2010) and 1524kg/m^3 (Chen, 1982) respectively. (See Eq. 18 – 20 for details in determining the digester's volume).
[4] The 21.3 l/kg-TS biogas yield of Adelekan (2012) for cassava peels and cattle dung in 1:1 ratio is low when compared to biogas yields of 600-650 l/kg-TS for AD of only cassava peels under optimal experimental conditions (Cuzin et al, 1992; Jekayinfa and Scholz, 2013). However, Adelekan (2012) noted a 15% increase in bioconversion efficiency (biogas production) when cattle dung is added to the cassava peels in a 1:1 ratio, which compares well with a 15% increase in bioconversion efficiency for cassava pulp and pig manure in a 1:1 ratio (Panichnumsin et al, 2010). Thus, the biogas yield considered in this study was estimated from the optimal biogas yield from cassava peels (600-650 l/kg-TS) and 15% increase in bioconversion efficiency to be 725 l/kg-TS.

$$\text{Volume of digester} = V_{gas} + V_{dig} \tag{18}$$

$$V_{dig} = t \times V_{dm} \tag{19}$$

$$V_{dm} = V_{cassava\ peels} + V_{cattle\ dung} + V_{water} \tag{20}$$

Where: V_{gas} - gas volume in digestion chamber (m^3)

V_{dig} - slurry volume in the digestion chamber (m^3)

t - retention time of slurry in the digester (days)

V_{dm} - the daily volume of slurry (m^3/day)

$V_{cassava\ peels}$, $V_{cattle\ dung}$ and V_{water} - the daily volumes of cassava peels, cattle dung and water respectively (m^3)

The gas volume in the digestion chamber (V_{gas}) was estimated as 10% of the digester volume (Samer, 2012), and an external storage vessel for the gas was assumed and factored in the costing.

Purification of the Anaerobic Digestion Generated Biogas and the Power Generation (for the Cassava Flour mills) Processes Modelling

According to Adelekan (2012), the generated biogas will have an average CH_4 content of 65.1% by volume. Although details on the other components of the biogas were not given, it was noted that traces of other gases, besidesCO_2, were present. To incorporate the potential economic impacts of cleaning the generated biogas for power generation, the composition was specified at volume composition of 64% vol. CH_4, 36% vol. CO_2 and 670–2500 ppmv H_2S (Quah and Gilles, 1981). In the modelling of the gas cleaning process in Aspen Plus®, water scrubbing with similar process conditions as in the POME biogas cleaning (see section 4.2.2.2), was implemented, to result in the safe H_2S limit of 1000ppm (Tong and Jaafar, 2005).

In the power generation process model, the generated biogas was utilised in generating electric power via a gas-engine generator which was modelled in Aspen Plus using similar procedure as previously described in section 4.2.2.2 (Gas-engine route). However, no thermal energy in the form of steam or hot water was required in the CF process, hence the turbine discharge stream pressure was specified as 2 bar to maximise the energy recovery from the combustion gases in the Aspen model.

Pre-treatment of the Generated Digestate's from Anaerobic Digestion of Cassava peels/Cattle dung (for Biofertiliser Purposes) Process Modelling

Considering the lack of literature on treatment of digestate from AD of cassava peels/cattle dung for purposes of biofertiliser application, the proposed treatment method of Owamah *et al*. (2014) was adopted, as their AD feedstock (human excreta and household food waste) is similar in biological loading to the cassava peels/cattle dung substrate under this study (see details in section 5.1.1.1). Hence, the digestate from each batch of the AD process was treated by holding in a tank for an extra period of 60 days, as the considered AD temperature of 32-40 ^oC was in the mesophilic range and batch period was 30 days.

5.2.2.2 *Gasification of the Cassava peels/woodshaving/sawdust to Cassava Flour Mill's Energy Process: Modelling Basis and Approach*

The process modelling of the gasification route was based on the study of Serpagli *et al.* (2010b). In the study, the selected gasification power system was comprised of a downdraft gasifier, gas cleaning and cooling system, gas engine generator, and hot air generator. The detailed gasification power system equipment list is given in Appendix B2. The study estimated that gasification of the adopted feedstock mix [blend of wood shavings/sawdust (in 7:3 weight proportion) and dried cassava peels in a 1:1 weight proportion] could generate 500m^3 syngas (with a calorific value of 4605.48kJ/m^3) per 200 kg biomass-mix (at dry weight of 20% moisture). Syngas was thus generated at a rate of 120kW and 100kW, gross and net electricity respectively, by means of a gas-engine generator. The material and energy balances of the gasification process were drawn up in Microsoft Excel, for the capacities of 1317.3 and 2970.5 kg cassava peels/day for the semi-mechanised CF and mechanised CF mills' gasification to in-house energy facilities respectively.

5.2.3 Economic Assessment of the Cassava Flour mill's Peels Residue Conversion to In-house Energy Processes

In the economic assessment of the AD and gasification processes, utilising peels residue of the CF mills for in-house energy generation, the approach and economic conditions were the same as for the in-house energy generation in CPO mills (see details under section 4.2.4). Details on the economic appraisal of nonconventional components and products are presented below.

5.2.3.1 *Appraisal of Unconventional Components/Products in the Anaerobic Digestion of Cassava peel/Cattle dung to Cassava Flour Mill's Energy Route*

The cost of the non-conventional anaerobic digester (VacVina digester) was estimated by scale-up of capital costs from smaller unit of 7m^3 capacity as shown in Appendix B1. Likewise, the investment cost of digestate treatment was estimated as the cost of two storage "brick-concrete" tanks (each the same size as the digester), operated in alternating shifts, as the digestion period was 30 days per batch, while the digestate treatment period was 60 days per batch.

It has been shown that the nutrients and composition of digestate from an AD process is dependent on the substrate, the source of AD microorganisms, and the type and configuration of the digester (Garfi *et al.*, 2011). Thus, the true benefits of a given digestate can be best assessed experimentally. However, due to lack of literature on the benefits of the digestate from AD of cassava peel/cattle dung, the price of the digestate as a biofertiliser was estimated from related literature, and an assumption of the digestate being able to replace fertiliser in farming with the same improvement in the yield of crops. Wirsiy (2013) identified a digestate to farmland density of 2.5 kg/m^2 (25 tons/ha) as the optimal digestate application for garden huckleberry (*Solanum scabrum*) farmlands. However, information on the improvement in huckleberry yield when conventional fertiliser is applied was not provided. Thus, available yield improvement data (with fertiliser application) for a related vegetable, garden egg or African eggplant's (*Solanum aethiopicum)* was adopted. Hornal *et al*. (2007) estimated the average cost of fertilizer requirement in garden egg farming at $132/ha with an average yield of 8.432 tons/ha. Under the assumptions that the impact of digestate on garden huckleberry farming is same as on garden egg farming, and can substitute fertilizer with the same increase in yield, the price of digestate would be $132/25tons in the year 2007 updated to $450/25 tons in 2014. Hence the unit price of $18/ton considered for the digestate from the AD of cassava peels/cattle dung under study.

5.2.3.2 *Appraisal of Unconventional Components in the Gasification of Cassava peel/Wood shaving/sawdust to Cassava Flour Mill's Energy Route*

The detailed equipment cost estimates for the gasification route were based on cost data from Serpagli *et al*. (2010b). The costs were adjusted for the different years using the Chemical Engineering Plant Cost Index (CEPCI) as shown in Equation 21 and capacities were then adjusted using the sixth-tenths-factor rule (described in Equation 22) as most of the equipment are non-conventional and their exponential factors are not available in literature (Peters and Timmerhaus, 2003). Details on the large scale (mechanised CF scale) equipment cost estimation (as an illustration) is presented in Appendix B2.

$$\text{Present cost} = \text{Original cost } \times \left[\frac{\text{CEPCI at present time}}{\text{CEPCI at time original cost was obtained}}\right] \tag{21}$$

$$\text{Cost of equipment A} = \text{Cost of equipment B} \times \left(\frac{\text{Capacity of A}}{\text{Capacity of B}}\right)^{0.6} \tag{22}$$

5.3 Results and Discussion

The estimated economic parameters and associated assumptions for the AD-to- energy route and the gasification route are given in Appendix B5 and B6 respectively.

5.3.1 Technical and Economic Performances of the Anaerobic Digestion (AD) of Cassava peels/cattle dung to Cassava Flour Mill's In-house Energy Models

5.3.1.1 *Technical Performance of the Anaerobic Digestion (AD) of Cassava peels/cattle dung to Cassava Flour Mill's In-house Energy Models*

The technical performance results of the CF mill's AD route for in-house energy are summarised in Table 5-5. The results (presented in Table 5-5) showed that, the semi-mechanised and mechanised CF mills' AD to energy facilities generated net power of 90 and 210 kW respectively, besides providing biogas for their respective process drying operations. In addition, 99.5 and 93.0% of the net generated power by the semi-mechanised and mechanised CF mills' AD energy facilities are available for export power purposes. The estimated biogas consumption rate of 0.73 and 0.74 m^3/kWh (estimates from results presented in Table 5-5) for the semi-mechanised and mechanised CF mills' AD to energy facilities (respectively) compare fairly with reported biogas (composition of 54-70% CH_4) consumption rate of 0.41-0.55 m^3/kWh for gas-engine generators (Lim, 1988).

Table 5-5: Estimated Technical performance of the anaerobic digestion of cassava peels/cattle dung to cassava flour (CF) mills in-house energy process models

Parameter	Estimate for semi-mechanised CF AD facility	Estimate for mechanised CF AD facility
Rate of generating biogas (m^3/day)	1910	4310
Gross power generated (kW)	100	230
Net electric power (kW) [1]	90	210
CF process electricity (kW)	0.5	15.0
Export electric power (kW)	91.5	195.0
Biogas (fuel) used by cassava meal dryer (m^3/day)	100	204
Digestate (tons/yr)	540	2390

[1] Net electric power determined as Gross power minus the sum of all the entire process' power demands (power required in biogas generation, cleaning & storage, and electric power generation).

5.3.1.2 *Economic Performance of the Anaerobic Digestion of Cassava peels/cattle dung to Cassava Flour Mills In-house Energy Process Models*

5.3.1.2.1 Capital Investment of the Anaerobic Digestion of Cassava Peels/Cattle dung to Cassava Flour Mills In-House Energy Process Models

The Total Capital Investment (TCI) and Specific Capital investment (SCI) of the AD-to-power processes are shown in Figure 5-3. From the results (Figure 5-3), TCI of $531809 and $932652 were noted for the semi-mechanised and mechanised CF mills' AD facilities respectively. Also, SCI of $5163/kW and $3985/kW were estimated for the semi-mechanised CF and mechanised CF mill's AD facilities respectively (see Figure 5-3). The referred SCIs compared favourably with adjusted estimate of $2880/kW-$3655/kW for a food-waste AD gas-engine power plant by Mott (2011). The biogas generation section contributed to 9.0 and 10.2% of the TCI for the semi-mechanised and mechanised CF mills' AD energy facilities respectively (as shown in Figure 5-3). The referred section accounted for 10.1 and 12.0% of the installed equipment cost for the semi-mechanised and mechanised CF mills' AD energy facilities respectively (estimated from result presented in Figure 5-3). On the other hand, the power generation section accounted for 60 and 56% of the installed equipment costs for the semi-mechanised and mechanised CF mills' AD energy facilities respectively (estimated from result presented in Figure 5-3). This suggests the power generation section as the most expensive section of the facility.

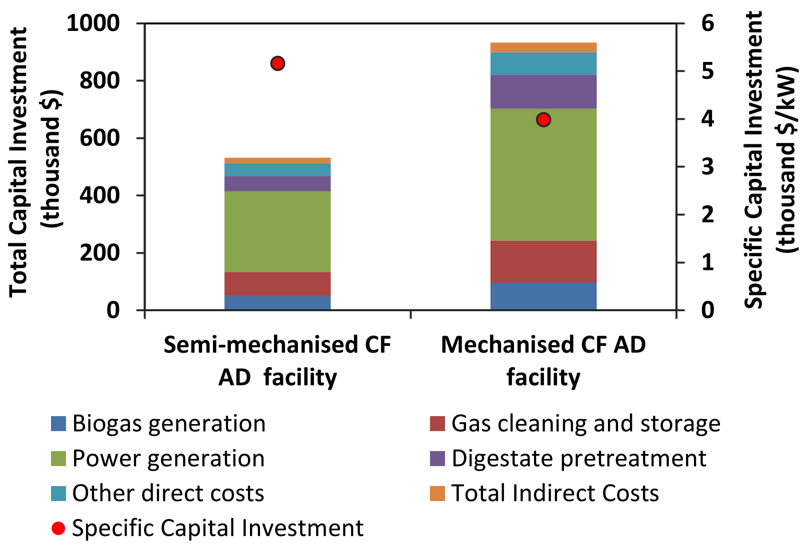


Figure 5-3: Breakdown of Total Capital Investment for the anaerobic digestion of cassava peels/cattle dung to cassava flour mill's process power models

5.3.1.2.2 Operating Cost of the Anaerobic Digestion of Cassava peels/cattle dung to Cassava Flour Mills In-house Energy Process Models

Figure 5-4 shows the breakdown of the annual Total Operating Costs (TOC) and the Specific Operating Costs (SOC) for the CF mills' AD-to- power processes. TOCs of $67779 and $84298, with corresponding SOCs of $0.091/kWh and $0.050/kWh, were noted for the semi-mechanised and mechanised CF mill's AD energy facilities respectively (see Figure 5-4). This suggest that the TOC of the mechanised CF mill's AD energy facility was higher by 19.6% when compared to that of the semi-mechanised facility, which can be attributed to the higher capacity of the mechanised facility (234 kW) as compared to the latter's (92 kW). On the other hand, the SCI of the mechanised facility suggest a decrease of 44.8% in the operating cost, when compared to the SOC of the semi-mechanised CF AD energy facility. In the models, the same equipment for the semi-mechanised facility were scaled up for the mechanised CF AD facility (with the exception of only the biogas digesters which were multiples for the larger facility). Thus, the 44.8% difference in SOC is most likely due to the benefit of economies of scale.

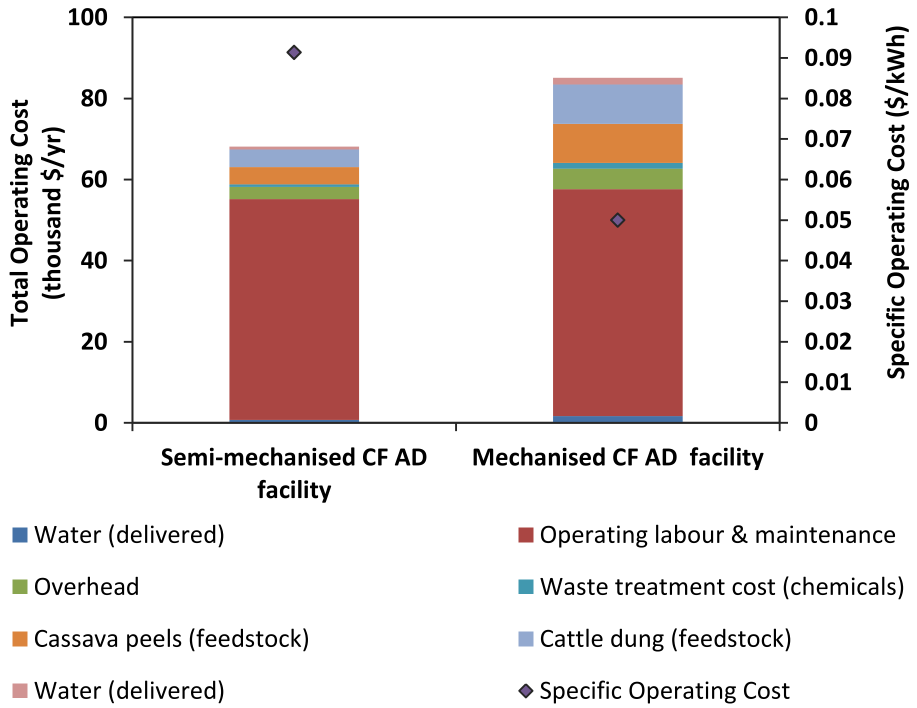


Figure 5-4: Total and Specific Operating Costs for anaerobic digestion of cassava peels/cattle dung to cassava flour mills process power models

5.3.1.2.3 Profitability Assessment of the Anaerobic Digestion of Cassava peels/cattle dung to Cassava Flour Mills In-House Energy Process Models

Table 5-6 summarises the result of the profitability assessment of the AD processes for the private investor financing [60% loan (at 24% interest rate) and 40% equity (at 40% interest rate), having weighted nominal discount rate of 30%]. In the economic assessment, the digestate and biogas for the cassava meal dryer (by products of the process) were considered as revenue sources at fixed prices of $0.672/m^3 and $18/ton respectively (see details in Appendix B3). The results (Table 5-6) showed at the grid power prices of $0.207/kWh and $0.348/kWh, none of the CF Mill AD to in-house energy facilities (as modelled in the study) achieved the expected IRR of 30%. The mechanised CF AD facility was the most promising option with an IRR of 24.8% at the grid power price of $0.348/kWh.

Table 5-6: Private investor financing results for the cassava flour (CF) mill's anaerobic digestion (AD) to in-house energy process models

Parameters	semi-mechanised CF AD facility		mechanised CF AD facility	
	$0.207/kWh	$0.348/kWh	$0.207/kWh	$0.348/kWh
NPV (million $)	-1.11	-0.71	-1.39	-0.49
IRR (%)	5.3	16.1	14.1	24.8
Payback period (yrs)	12.4	8.5	9	6

However, under the CF processor as the investor financing [60% loan (at 24% interest rate) and 40% equity (at 0% interest rate), having weighted nominal discount rate of 14.4%], it was noted that the processes, with the exception of the semi-mechanised CF AD facility at the grid power price of $0.207/kWh, attained IRRs greater than the minimum expected 14.4% (see Table 5-7). Thus suggesting the processes are economically viable under the CF mill operator financing (as the investor) conditions.

Table 5-7: Cassava flour (CF) processor (as the investor) financing structure's results for the CF mill's AD to in-house energy process models

Parameters	semi-mechanised CF AD facility		mechanised CF AD facility	
	$0.207/kWh	$0.348/kWh	$0.207/kWh	$0.348/kWh
NPV (million $)	-0.79	0.175	-0.05	2.12
IRR (%)	5.3	16.1	14.4	24.8
Payback period (yrs)	12.4	8.5	9	6

The minimum expected power prices for the economic viability of the CF AD to in-house energy facilities, under the private investor (nominal discount rate of 30%) and the CF mill operator as the investor (nominal discount rate of 14.4%), are given in Figure 5-5. It can be noted from the results (Figure 5-5) that, under the private investor scheme, the expected power prices for the mechanised ($0.426/kWh) and semi-mechanised ($0.602/kWh) CF AD facilities were higher than the maximum grid power price by 18.3 and 42.2% respectively. This suggests the mechanised CF AD process could be viable (under the private investor financing) when the environmental benefit of bioelectricity, corresponding to suggested 20% increment in fossil based power price (Leibbrandt ,2010), is taken into consideration. On the other hand, under the CF mill operator (as investor) financing scheme, the power prices for the semi-mechanised ($0.322/kWh) and mechanised ($0.211/kWh) CF AD facilities were lower by 7.47 and 39.4% than the maximum grid power price of $0.348/kWh (see Figure 5-5). Thus suggesting the processes are economically viable under the CF mill operator (as investor) financing structure.

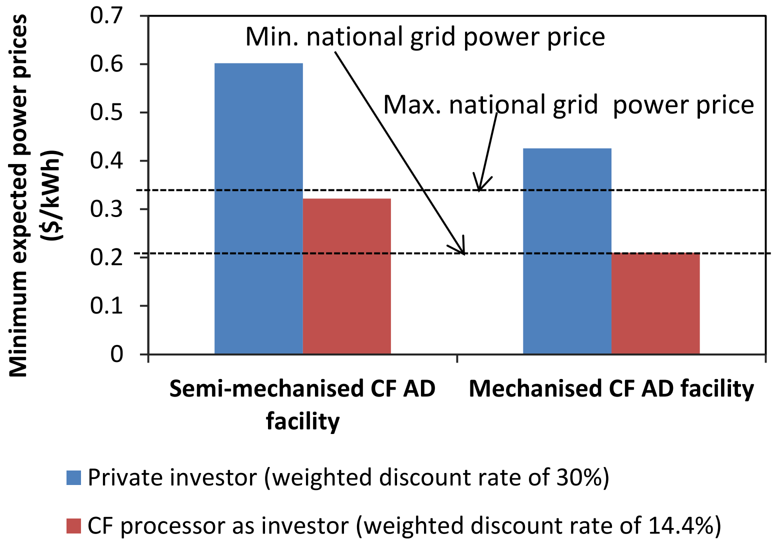


Figure 5-5: Minimum expected power prices for Cassava Flour (CF) Mill's anaerobic digestion (AD) to in-house energy processes, for under the private investor (discount rate of 30%) and the CF mill as the investor (discount rate of 14.4%) financings structures

The minimum expected CF mill's power prices, under an assumption of all the generated surplus power being sold at prevailing grid price of $0.348/kWh, for the private investor financing and CF mill processor financings are summarised in Figure 5-6. The results (Figure 5-6) revealed under the CF mill investor financing scheme [60% loan (at 24% interest rate) and 40% equity (at 0% interest rate), weighted nominal discount rate of 14.4%], the CF mill's power could be supplied at no cost ($0/kWh), as selling of the surplus generated power at the grid power price of $0.348/kWh would be sufficient to make the AD in-house energy processes economically viable. Furthermore, the $0/kWh power prices for the CF mills result in the IRRs of the CF mills being greater than the expected minimum IRR of 30%

(see Figure 5-6). On the other hand, under the private investor financing [60% loan (at 24% interest rate) and 40% equity (at 40% interest rate), having weighted nominal discount rate of 30%], the expected power prices of the CF mills result in the CF mills being unviable with IRRs of 0% noted in all cases (see Figure 5-6). Thus, from the perspective of profitability of the CF process, the AD in-house energy approach for the CF mills is economically viable and beneficial under the CF mill operator financing structure.

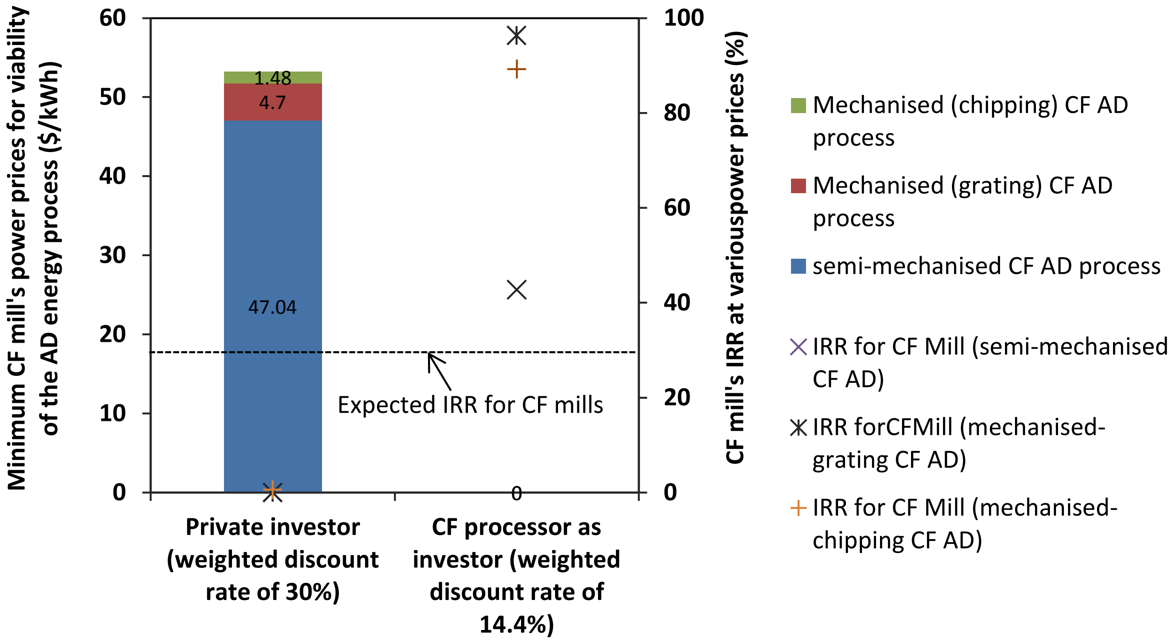


Figure 5-6: Minimum expected cassava flour (CF) mill's anaerobic digestion (AD) route's in-house power prices (under assumption of all surplus generated power sold at prevailing grid price of $0.348/kWh), for private investor/CF mill investor financings, and their corresponding impacts on the CF mill's Internal Rate of Return (IRR)

The economic analysis of the various grant-equity funding [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)] for the AD in-house energy processes is shown in Figure 5-7. The results (Figure 5-7) revealed that, selling the generated power at the prevailing grid power prices (0.207-0.348/kWh) result in both the semi-mechanised CF AD and mechanised CF AD facilities achieving positive NPVs [at grant contributions between 40-70% (remaining 60-30% financing from equity)], suggesting the processes are economically viable under the referred grant-equity funding scheme.

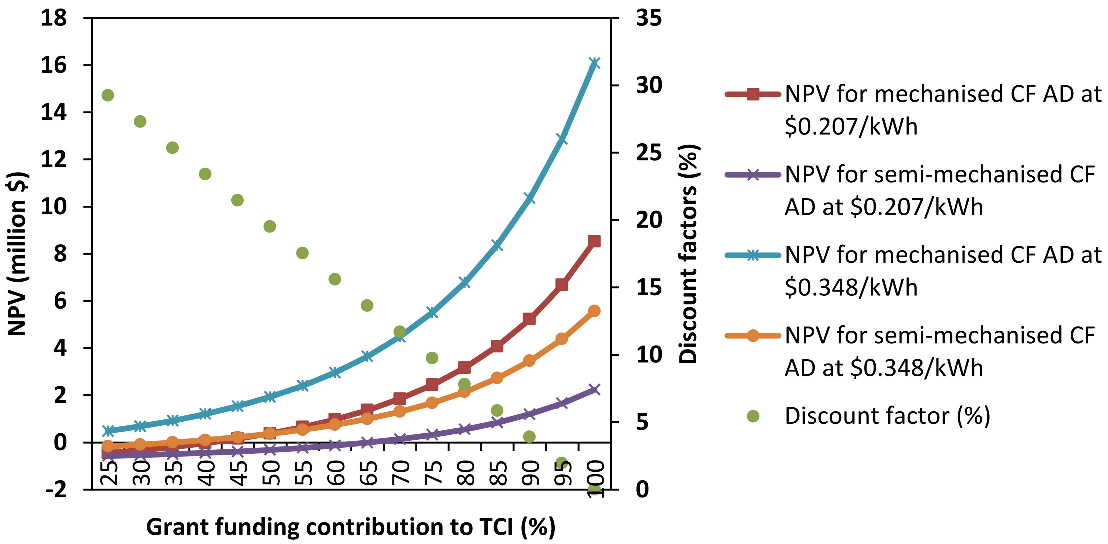


Figure 5-7: Variations in Net Present Values to changes in grant-equity financing schemes for the anaerobic digestion of cassava peels/cattle dung to cassava flour mill's in-house energy process models

5.3.2 Technical and Economic Performances of the Gasification of Cassava peels/wood shavings/sawdust to Cassava Flour Mill's In-House Energy Models

5.3.2.1 *Technical Performance of the Gasification of Cassava peels/wood shavings/sawdust to Cassava Flour Mill's In-House Energy Models*

The results of the technical performances of the gasification route are summarised in Table 5-8. The result indicated a net power of 15 and 47 kW could be generated by the semi-mechanised CF gasification and mechanised CF gasification energy facilities, respectively, which were adequate for the semi-mechanised (0.5 kW), mechanised-grating (3.8 kW) and mechanised-chipping (15.0 kW) CF mills' power demands. The relatively small excess power in all the scenarios aforementioned could be exported for small load duties such as community or household lighting.

Table 5-8: Technical performance of the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy process models

Parameter	semi-mechanised CF gasification facility	mechanised CF gasification facility
Gross power generated (kW) [1]	18	57
Net electric power (kW) [1]	15	47

[1] Estimates adapted from gasification of same feedstock-mix (cassava peels to wood shavings/sawdust at 1:1 proportion with wood shavings and sawdust at 7:3 proportions) yielding 500 m^3 syngas/200kg biomass mix (at calorific value of 4605.48 kJ/m^3) generating 120kW and 100kW gross and net electricity respectively (Serpagli et al., 2010b).

5.3.2.2 *Economic Performance of the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy models*

5.3.2.2.1 Capital Investment of the Gasification of Cassava peels/wood shavings/sawdust to Cassava Flour Mill's In-House Energy Models

Figure 5-8 highlights the Total Capital Investment (TCI) and Specific Capital Investment (SCI) of the gasification to in-house energy models. TCIs of $322880 and $436740, with corresponding SCIs of $17700/kW and $7700/kW, were noted for the semi-mechanised CF gasification and mechanised CF gasification facilities respectively. Estimated 2010 specific installed capital cost for biomass gasifier power technologies ranged between $2100-5800/kW, adjusted to $2368-6541/kW in 2014 (IRENA 2012). The installed equipment cost excluding the cassava meal dryer amounted to $142543 and $201318 (estimated from result presented in Figure 5-8), which translate to specific capital costs of $7830/kW and $3560/kW for the semi-mechanised CF gasification and mechanised CF gasification facilities respectively. Thus the referred estimates of the study compares well with literature although the medium scale facility was out of the range by an excess of 16.5%. This could be due to the high reliance of the cost of gasification power technologies on the specific process considered (US EPA, 2007).

Also, a significant contribution of economies of scale was noted as there was 54.6% reduction in the specific capital cost for the mechanised CF gasification facility (56.57 kW) when compared to that of the semi-mechanised gasification facility (18.2 kW) (see Figure 5-8). Furthermore, the significant sections of the equipment was the power generation section which contributed 33.0 and 34.7%, followed by the gasification section that accounted for 26.9 and 33.3% of the total installed costs for the semi-mechanised CF gasification and mechanised CF gasification facilities respectively (estimated from results presented in Figure 5-8).

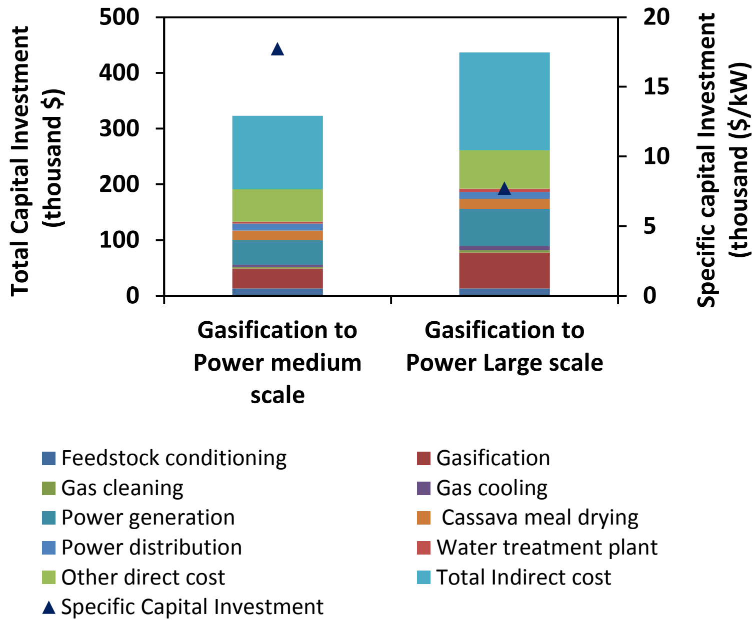


Figure 5-8: Breakdown of Total Capital Investment for the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy process models

5.3.2.2.2 Operating Costs of the Gasification of Cassava peels/wood shavings/sawdust to Cassava Flour Mill's In-House Energy Models

The results of the Total Operating Cost (TOC) and Specific Operating Cost (SOC) for the gasification to power processes are given in Figure 5-9. For the semi-mechanised CF gasification capacity (net power of 15.17 kW), TOC of $84480 and SOC of $0.639/kWh were noted (see Figure 5-9). On the other hand, TOC of $94000 and SOC of $0.229/kWh were obtained for the mechanised CF gasification facility (net power of 47.14 kW) (see Figure 5-9). Upon manipulating and adjusting the operating cost data of the referred study of Serpagli *et al.* (2010b) for a similar 64.77 kW (net power) facility, SOC of $0.145/kWh was obtained suggesting a trend of reduction in the SOC as the plant power capacity (power generation) increases. Furthermore, a similar trend was noted in the operation and maintenance costs. For this study, specific operation and maintenance costs of $0.556/kWh and $0.180/kWh were noted for the semi-mechanised CF and mechanised CF gasification facilities respectively, while that obtained for the referred study was $0.018/kWh. Thus the most likely factor for the trends above is the benefits of economies of scale as the labour requirement of the process is not directly proportional, but rather less sensitive to the power output.

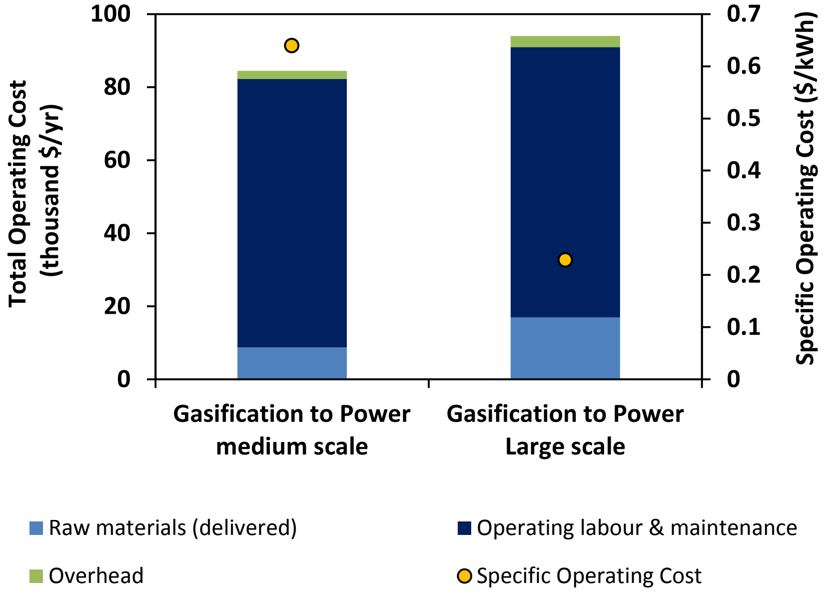


Figure 5-9: Total and Specific Operating Costs for the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy process models

5.3.2.2.3 Profitability Assessments of the Gasification of Cassava peels/wood shavings/sawdust to Cassava Flour Mill's In-House Energy Models

Table 5-9 shows the economic performance of the gasification in-house energy route, under the private investor financing [60% loan (at 24% interest rate) and 40% equity (at 40% interest rate), having weighted nominal discount rate of 30%]. The result (given in Table 5-9) suggests both the semi-mechanised CF gasification and mechanised CF gasification facilities investigated were not economically viable for the expected IRR of 30%. However, the mechanised CF gasification facility showed an improvement in the economic performance with IRR of -3.71% and 11.42% at the prevailing grid power prices of \$0.207/kWh and \$0.348/kWh respectively (see Table 5-9). These findings corroborates with Serpagli *et al.*'s (2010b) finding of the gasification power facility at 200 kg/hr feedstock capacity (net power of 64.77kW) being promising with an IRR of 17% in the year 2010 (for an expected IRR of 22%). Their relatively high attained IRR as compared to those obtained in this study could be mainly credited to their assessment based on Total Investment Costs secured from local banks at a relatively low interest rate of 22% in 2010, as compared to the high average interest rate of 30% for the assumed funding scheme of 60% loan and 40% equity under this study, as well as the benefits of economies of scale as noted from the SCI and SOCs above.

Table 5-9: Results for Private Investor financing scheme of the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy process models

Parameters	Medium (Electricity s.p per kWh)		Large (Electricity s.p per kWh)	
	0.207	0.348	0.207	0.348
NPV (thousand $)	-701.67	-614.71	-665.48	-440.30
IRR (%)	-	-	-3.7	11.4
Payback period (yrs)	-	-	-	10

The results of the economic performances for the gasification processes, under the operator of the CF mill as the investor financing [60% loan (at 24% interest rate) and 40% equity (at 0% interest rate), weighted nominal discount rate of 14.4%], are summarised in Table 5-10. It was noted that, all the gasification processes (as modelled) still remained unviable under the CF mill operator financing (for an expected IRR of 14.4%). The mechanised gasification process was the most promising option to being economically viable with an IRR of 11.4% (see Table 5-10).

Table 5-10: Cassava flour (CF) processor (as the investor) financing structure's results for the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy process models

Parameters	semi-mechanised CF gasification energy facility		mechanised CF gasification energy facility	
	$0.207/kWh	$.348/kWh	$0.207/kWh	$0.348/kWh
NPV (thousand $)	-997.52	-786.55	-664.48	-141.27
IRR (%)	-	-	-3.7	11.4
Payback period (yrs)	-	-	-	10

Figure 5-10 summarises the minimum expected power prices required to make the gasification processes economically viable, under both private investor (nominal discount rate of 30%) and the CF mill operator as the investor (nominal discount rate of 14.4%) financing. It can be seen (from Figure 5-10) that all the minimum expected power prices were higher than the maximum grid power price of $0.348/kWh. Furthermore, with the exception of the mechanised CF gasification facility whose minimum expected power price was higher by 10.3% than the grid price of $0.348/kWh, all the other processes' minimum expected power prices were higher by 46.7-77.9% than the maximum grid price ($0.348/kWh) (see Figure 5-10). This suggests under consideration of Leibbrandt's (2010) recommended increment of 20% over fossil based power price to account for environmental benefits of bioelectricity, only the mechanised CF gasification process becomes viable under the funding conditions of the CF mill operator as the investor scheme.

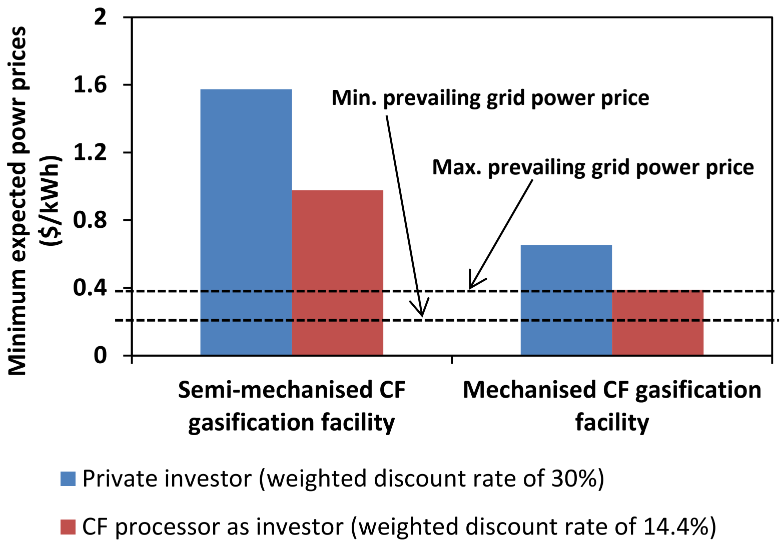


Figure 5-10: Minimum expected power prices for Cassava Flour (CF) Mill's gasification to in-house energy processes, for private investor (discount rate of 30%) and the CF processor as the investor (discount rate of 14.4%) financings structures

In addition, the outcome of the sensitivity assessment on grant-equity funding schemes (shown in Figure 5-11) revealed the semi-mechanised CF gasification facility was still not economically viable even under 100% grant funding for the base power prices of \$0.207/kWh and \$0.348/kWh. However, the mechanised CF gasification facility attained positive NPVs of \$92523 (at 95% grant contribution) and \$8717 (at grant contributions of 50%) for the power prices of \$0.207/kWh and \$0.348/kWh respectively. Hence, confirming the above noted impact of the higher interest rate and benefits of economies of scale on the profitability of the process.

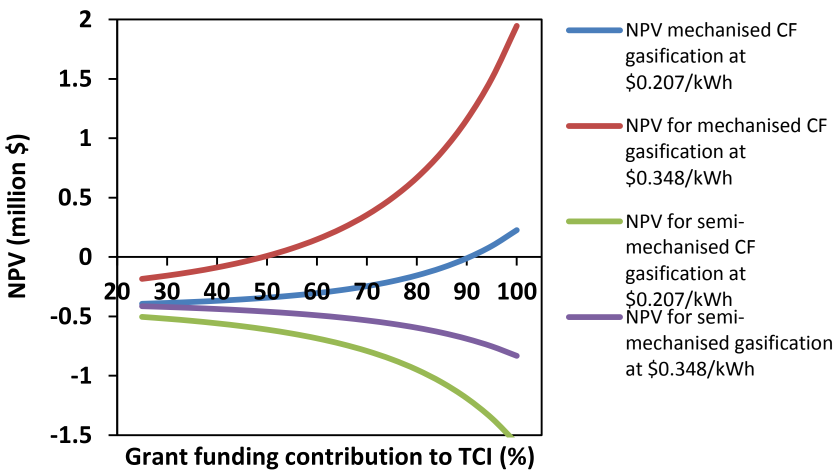


Figure 5-11: Variations in Net Present Values to changes in grant-equity financing schemes for the Gasification of cassava peels/wood shavings/sawdust to cassava flour mill's in-house energy models

5.4 Conclusions

The economic feasibility of gasification and anaerobic digestion (AD) of cassava peels (residue) to power and syngas/biogas, with an outlook of supplying the electric and dryer heat energy demands of a semi-mechanised (medium capacity of 4.8tons cassava/day) and mechanised (large capacity of 10 tons cassava/day) cassava flour mills, were assessed. In the AD and gasification approaches, cattle dung and wood shavings/sawdust (respectively) as additional feedstocks were required for technical feasibility.

The models showed both scenarios could generate enough syngas/biogas to meet the mills' electric power and dryer energy requirements, besides providing surplus power for export purposes. The surplus power in the AD processes (as modelled) were 91.5 kW for the semi-mechanised CF and 194.53 kW for the mechanised CF capacities, while their respective gasification processes (as modelled) attained surplus power of 14.67 and 32.7 kW.

The AD scenarios were the most promising options with regards to economic viability, with expected power prices ranging between $0.426-0.602/kWh under private investor financing [60% loan (at an interest rate of 24%) and 40% equity (at an assumed interest rate of 40%), weighted nominal discount rate of 30%], which were of the same order of magnitude as the prevailing grid price of $0.207-0.348/kWh. On the other hand, under the private investor financing, the gasification scenarios' expected power prices of $1.573/kWh (semi-mechanised CF capacity) and $0.653/kWh (mechanised CF capacity) suggests its economic viability is highly dependent on the capacity, which was mainly due to higher impacts of economies of scale on gasification processes (US EPA, 2007).

Additionally, under grant-equity financing [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)], the AD processes were economically viable at 40 & 70% grant contributions (remaining 60 & 30% financing by equity), while the mechanised gasification process was viable at 50 & 95% grant contribution (remaining 50 & 5% financing by equity). Hence, the high interest rate on loans (24%) is a major determining factor for economic viability of bioenergy processes. Thus, promoting bioenergy processes must therefore focus on economic interventions such as tax exemption or rebate policies, provision of soft loans or grant subsidies by the government or Development Financing Institutions to make bioenergy projects realisable under the economic context of Ghana.

Nonetheless, under conditions of the CF mill operator financing the energy processes [60% loan (at 24% interest rate) and 40% equity from the operator (at 0% interest rate), weighted nominal discount rate of 14.4%], with an outlook of securing energy for the CF process, the AD scenarios could supply power to the CF mills at no cost provided the surplus power could be sold at the maximum grid price of $0.348/kWh. This scheme could result in the CF mills attaining higher IRRs ranging between 42.8-96.3% (compared to an expected IRR of 30%). Thus, suitability of bioenergy to be integrated in cassava flour processing is possible under economic influences in SSA. Although bioenergy production from the process biomass residues is still at an early stage of development, future application will require governmental incentives that help to overcome economic challenges such as tax exemptions, appreciable feed-in-tariff for bioenergy, and soft loans or grant supports for bioenergy projects to be cost-effectively implemented.

6 OUTCOMES OF MODELLED FOOD PROCESSES

Although the developed food process models are applicable to any of the food processing nations in SSA, the economic models were based on the year 2014 economic conditions of Ghana and therefore specific to only Ghana. The above was undertaken to provide a common economic assessment conditions for the three food processes under study. Economic variables [Total Capital Investment (TCI) and Total Production Cost (TPC)], and economic viability indicators [Net Present Value (NPV), Internal Rate of Return (IRR) and Payback-period (PB)] were evaluated based on cost data from literature or vendors' quotations.

Also, two financing schemes were considered for each food process: 1. Private Investor financing scheme of 60% loan from local banks and the remaining 40% as equity from an investor, having a weighted nominal discount rate of 30% (before accounting for inflation), which was based on 24 and 40% interest rates on loan and equity respectively (BoG, 2014). 2. Combinations of grant and equity financing schemes (i.e. partial grant financing and the remaining financing from equity), in which the grant component was discounted at 0% and the equity component was discounted at 40% (in nominal terms). In both financing schemes, all future monetary projections were based on the national inflation rate of 15% (BoG, 2014). In the estimations of the TPC, labour requirement for all traditional processes was based on average household of 4 (GSS, 2008) and labour cost were estimated based on minimum wage of $2.106/day (as of 1st April, 2014). On the other hand, skilled labour costs were informed by labour cost data from www.mywage.org.

Chapters 4 and 5 addressed the gaps of the technical and economic feasibility of the advanced in-house energy integration in the Improved-Case (I/C) scenarios of the mechanised CPO, semi-mechanised CF and mechanised CF processes in Chapter 3. Considering the economic assessments of all the food processes were evaluated under a private investor financing (weighted nominal discount rate of 30%), the determined minimum expected power prices under the private investor financing (same conditions as private investor financing for the food processes with weighted discount rate of 30%) were considered in the economic assessment of the I/C scenarios for the mechanised CPO, semi-mechanised CF and mechanised CF processes.

Additionally, based on the technical and economic findings of the modelled advanced in-house energy processes in Chapters 4 and 5, the most promising in-house energy approach adopted for integration in the mechanised CPO process was the solid residues with efb addition approach (Scenario 2) (as described in Figure 4-3, section 4.2.2.1). This choice was based on the 100% in-house energy attainment and competitive expected power price of \$0.712/kWh (as detailed under sections 4.3.1.1 and 4.3.1.3). Likewise, the AD approach for in-house energy integration in the semi-mechanised and mechanised CF mills was selected due to the 100% attainment of the process dryer and electric energy demands, and the competitive expected power prices of \$0.602/kWh (semi-mechanised CF mill) and \$0.426/kWh (mechanised CF mill) (as detailed in sections 5.3.1.1 and 5.3.1.2.3).

The detailed energy demands and economic performances of the modelled food processes under study i.e. crude palm oil (CPO), cassava flour (CF) and maize flour (MF) and their related discussions are presented in this Chapter. Appendix B7 highlights the economic parameters and assumptions considered in the economic assessment of the food processes.

6.1 Energy and Economic Performances of the Crude Palm Oil (CPO) Processes

6.1.1 Energy Performances of the Crude Palm Oil Processes

The results of energy intensities for the CPO processes (shown in Figure 6-1) indicate a wide variation in the energy intensity (energy expended in the CPO production process given in MJ/kg CPO produced) of the processes modelled with the highest and least of 37.06 MJ/kg and 6.01 MJ/kg respectively. For the I/C scenarios, the energy intensity of the semi-mechanised level was higher than the energy intensities of the traditional and mechanised levels by 5.8 and 51% respectively (Figure 6-1). Likewise for the B/C scenarios, the energy intensity of the semi-mechanised level exceeded the energy intensities of the traditional and mechanised levels by 21.9 and 83.8% respectively (Figure 6-1). As previously indicated in section 3.3.1, this could be attributed to the low CPO yield of 22% for the semi-mechanised level as compared to the 28.0 and 31.3% for the traditional and mechanised levels respectively (presented in Table 3-4).

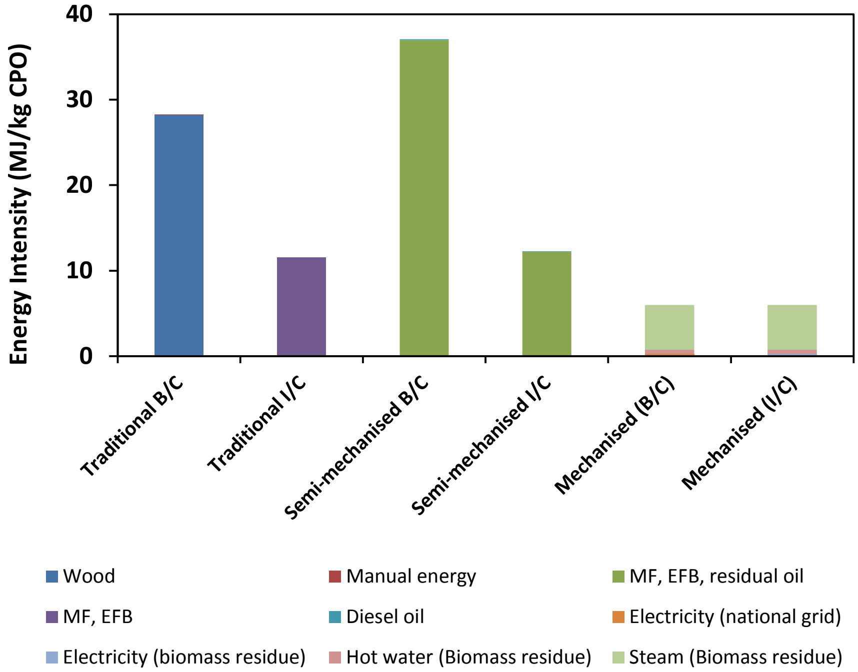


Figure 6-1: Energy demands in the various approaches (mechanisation levels and process energy sourcing) of processing crude palm oil as modelled

Also, the results (in Figure 6-1) revealed that the I/C scenarios generally expended less energy than their respective B/C scenarios. The energy demands of the traditional I/C process was lower than its B/C's by 40%, the semi-mechanised I/C's energy demands was lower than its B/C's by 33%, and the mechanised B/C and I/C had the same energy demands (see Figure 6-1). The high energy demands of the traditional and semi-mechanised B/C processes, when compared to that of their respective I/C processes (respectively), was mainly due to the low thermal efficiency of the tripod stoves (15%) for undertaking the most energy intensive unit operation of boiling fruits (sterilisation) as noted under section 3.3.1 (see details in the developed process flowsheets in Figure 3-2 and Figure 3-4 under section 3.3). Moreover, the consideration of an improved cook-stove with a thermal efficiency of 30%, as considered in the traditional and semi-mechanised I/C scenarios, contributed to the decrease in the energy demands of the traditional and semi-mechanised processes by over half that of their corresponding B/C scenarios (Figure 6-1). The mechanised B/C and I/C scenarios energy intensities were the same as a result of the same processing units and energy forms considered in both scenarios with only the sources of the energy being the differing factor.

In addition, biomass (process residues or wood) dominated the energy-mix for all the B/C processes, with contributions of 99.8, 99.7 and 95.4% of the total energy demands for the traditional, semi-mechanised and mechanised levels, respectively (as shown in Figure 6-1). Likewise, biomass (process residues) dominated the I/C scenarios energy-mix with contributions of 99.6, 99.4 and 100% of the total energy demands for the traditional, semi-mechanised and mechanised levels' respectively (as shown in Figure 6-1). Although the contribution of biomass energy in the Base-Cases (B/C) does not differ much from that of the corresponding Improved-Case (I/C) scenarios, substituting external energy such as wood fuel (in the traditional process) and national grid electricity (in the mechanised process) with the CPO mill's solid biomass residues was technically feasible as established from the process models of the I/C scenarios (see Figure 6-1).

6.1.2 Economic Performances of the Crude Palm Oil Processes

6.1.2.1 *Capital Investment for the Crude Palm Oil Processes*

Figure 6-2 presents the Total Capital Investments (TCI) and Specific Capital Investments (SCI) for the CPO processes as modelled under the study with the latter reported on the basis of per kg CPO produced. Note that, the TCI for traditional B/C & I/C and semi-mechanised B/C & I/C were small compared to that for the mechanised B/C and I/C, thus these have been multiplied by a factor of 100 to make them visible in the figure. A wide variation in TCI ranging $4464 - $17.746 million and SCI ranging $0.013-0.055/kg CPO were noted for the processes (shown in Figure 6-2). Also the semi-mechanised levels had the least SCI range of $0.013-0.019/kg CPO while the mechanised levels attained the highest range of $0.053-0.055/kg CPO (see Figure 6-2). In general, a trend of decreasing TCI from the traditional to semi-mechanised processes was noted while those of the mechanised levels were the highest (see Figure 6-2). At the traditional level, the TCI's of the B/C scenario was higher than the I/C's by 14.9%. In contrast, the TCI of the I/C scenarios for the semi-mechanised and mechanised levels were higher than their corresponding B/C's by 4.9% and 4.0% respectively (see Figure 6-2).

However, in comparing the SCIs for the B/C scenarios to that of their respective I/C scenarios, a decrease by 14.9% and 30.6% in the specific capital investment was attained by the I/C scenarios for the traditional and semi-mechanised levels (respectively), while an increase by 4.0% in the SCI of the mechanised I/C process can be noted (see Figure 6-2).

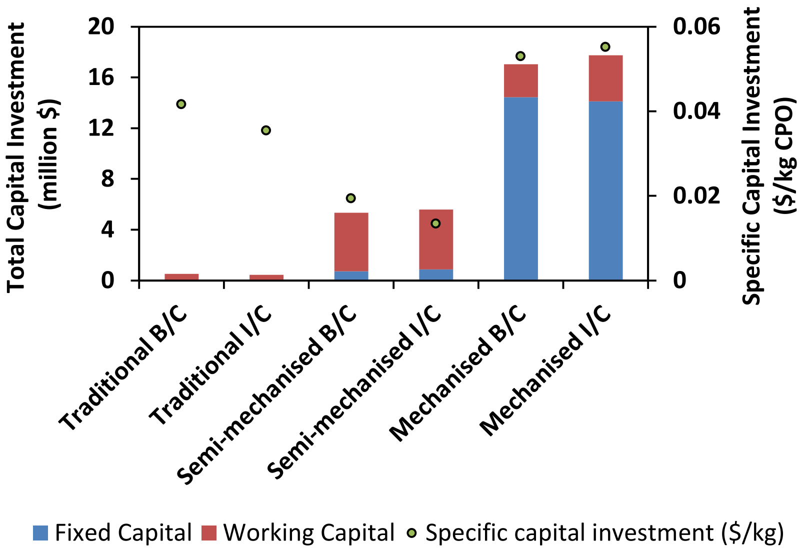


Figure 6-2: Total and Specific Capital Investment (TCI) for the various approaches (mechanisation levels and process energy sourcing) of processing crude palm oil as modelled (Note: the TCI for traditional B/C & I/C and semi-mechanised B/C & I/C were small compared to that for the mechanised B/C and I/C, thus these have been multiplied by a factor of 100 to make them visible in the figure).

Although the TCI of the semi-mechanised I/C scenario was higher than its corresponding B/C's, its SCI was lower than the latter's. This was mainly due to the higher oil extraction efficiency for the motorized digester-press technology adopted in the I/C process model (with a CPO yield of 0.33 kg CPO/kg FFB), as compared to the extraction efficiency of the 'digester with hand operated press' technology (with CPO yield of 0.22kg CPO/kg FFB) considered for the B/C scenario's model (see Table 3-4). On the other hand, similar oil extraction technologies, with the same oil extraction efficiencies, were considered in the models of the traditional/mechanised B/C scenarios and their corresponding I/C scenarios, hence the similar magnitude of differences noted for the comparisons of their B/C's TCI and SCI to their respective I/C's.

6.1.2.2 *Production Cost for the Crude Palm Oil Processes*

The Total Production Costs (TPC) and Specific Production Costs (SPC) for the CPO processes (with the latter on per kg CPO basis) are summarised in Figure 6-3. TPC ranging between $25138-$12.253 million and SPC ranges of $0.998-1.187/kg CPO were noted (as shown in Figure 6-3). Furthermore, the traditional level had the highest SPC range of $0.998-1.187/kg CPO while the mechanised level had the least range of $0.431-0.571/kg CPO (see Figure 6-3). For the B/C scenarios, the traditional level's SPC was higher than those of the semi-mechanised and mechanised levels by 15.3 and 63.7% respectively (see Figure 6-3).

Similarly for the I/C scenarios, the traditional SPC exceeded the SPC of the semi-mechanised and mechanised levels by 31.9 and 42.7% respectively (see Figure 6-3). Also comparing the TPC for the B/C scenarios to that of their respective I/C scenarios, a savings of 15.9% in the traditional I/C level's TPC, and 2.3 and 24.5% increase in the semi-mechanised and mechanised I/C scenarios TPCs respectively was noted (see Figure 6-3). Furthermore, when comparing the SPC for the B/C scenarios to that of their respective I/C scenarios, savings of 15.9% in the traditional I/C level's SPC, increase of 24.5% in the mechanised I/C level's SPC, and savings of 32.4% in the semi-mechanised I/C level's SPC was noted (see Figure 6-3). The referred trends could be attributed to the same reason given above for the similar trend under the comparison of the TCI and SCI for the CPO processes (given in section 6.1.2.1).

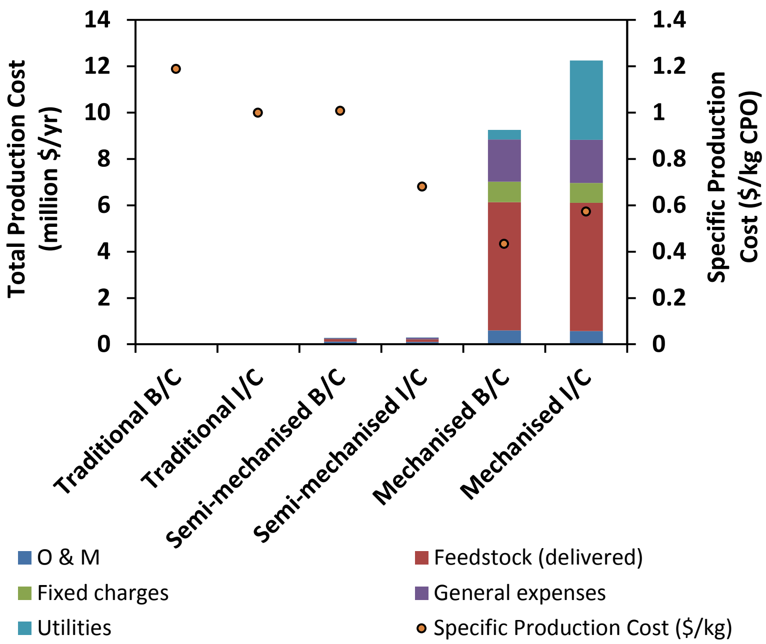


Figure 6-3: Total and Specific Production Costs for the various approaches (mechanisation levels and process energy sourcing) of processing Crude Palm Oil as modelled

6.1.2.3 *Profitability assessments of the Crude Palm Oil Processes*

The economic results of the private investor financing [60% loan (at an interest rate of 24%) and 40% equity (at an assumed interest rate of 40%), weighted nominal discount rate of 30%] for the CPO processes are summarised in Table 6-1. The results (shown in Table 6-1) revealed for the B/C scenarios, only the mechanised level's approach was economically viable with an NPV of $18.5 million and IRR of 47.2%. However under the suggested improved case (I/C) scenarios, the semi-mechanised and mechanised processes were the economically viable options with IRRs of 143% and 40.6% respectively (see Table 6-1). The high IRR of 143% was possibly due major contributions by higher CPO yield of 0.33 kg CPO/kg FFB, and the high savings in solid biomass residues (as a result of the improved cook-stoves high thermal efficiency of 30%) which increased revenues when sold as fuel for power generation or household cooking.

Table 6-1: Baseline economic results for the crude palm oil processing models

Parameter	Traditional		Semi-Mechanised		Mechanised	
	B/C	I/C	B/C	I/C	B/C	I/C
Capacity (tons CPO/yr)	25	25	275	417	21445	21445
Plant life (yrs)	5	5	10	10	15	15
Economic evaluations						
NPV ($)	-18367	-11215	-109334	301644	18500246	11501446
IRR (%)	-	-	-	143.0	47.2	40.6
Payback period (yrs)	-	-	-	1	2.7	3
Required CPO prices for IRR of 30% ($/ton)	950	856	810	500	500	569

N.B: Economic evaluations considered financing terms of 60% loan and 40% equity (with a weighted nominal discount rate of 30%)
* B/C – Base-Case scenarios; I/C – Improved-Case Scenarios

Under the mechanised processes, the required power price of $0.712/kWh for the in-house electricity from biomass residues (bioelectricity) still makes the mechanised I/C process economically viable with an IRR of 40.6%, although this is less than that of the B/C's 47.2% at national grid power price of $0.207/kWh. In addition, to attain the expected IRR of 30%, the prices of CPO under the I/C conditions must be $856/ton, $500/ton and $569/ton for the traditional, semi-mechanised and mechanised processes respectively, and for the B/C conditions must be $950, $810 and $500 for the traditional, semi-mechanised and mechanised processes respectively (as noted in Table 6-1). This gives a fair idea of how superior or close the processes are to meeting the present economic conditions when compared to the prevailing CPO price of $710/ton.

The assessment of grant-equity funding [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)] impacts on the economic performances of the traditional- B/C and I/C, and the semi-mechanised B/C scenarios (as shown in Figure 6-4) revealed the processes were still not viable even with 100% grant funding scheme. This implied their production cost ($0.431–1.187/kg) were high, and not justified by the CPO price of $0.71/kg CPO. The high production appears to be more dependent on collective impacts of mechanisation and process energy demands, and to a lesser extent on the feedstock cost. For instance, under assumptions of similar impacts of mechanisation for the semi-mechanised B/C and I/C level, both having their feedstock accounting for 42% of their TPCs, an improvement of 15% of energy efficiency is realised by replacing inefficient tripod stove with improved cook stoves, and as a result the I/C process became economically viable (IRR of 143%) (see Table 6-1). Therefore, mechanisation of the CPO process is economically rewarding when implemented together with improvement of the energy efficiency of the process.

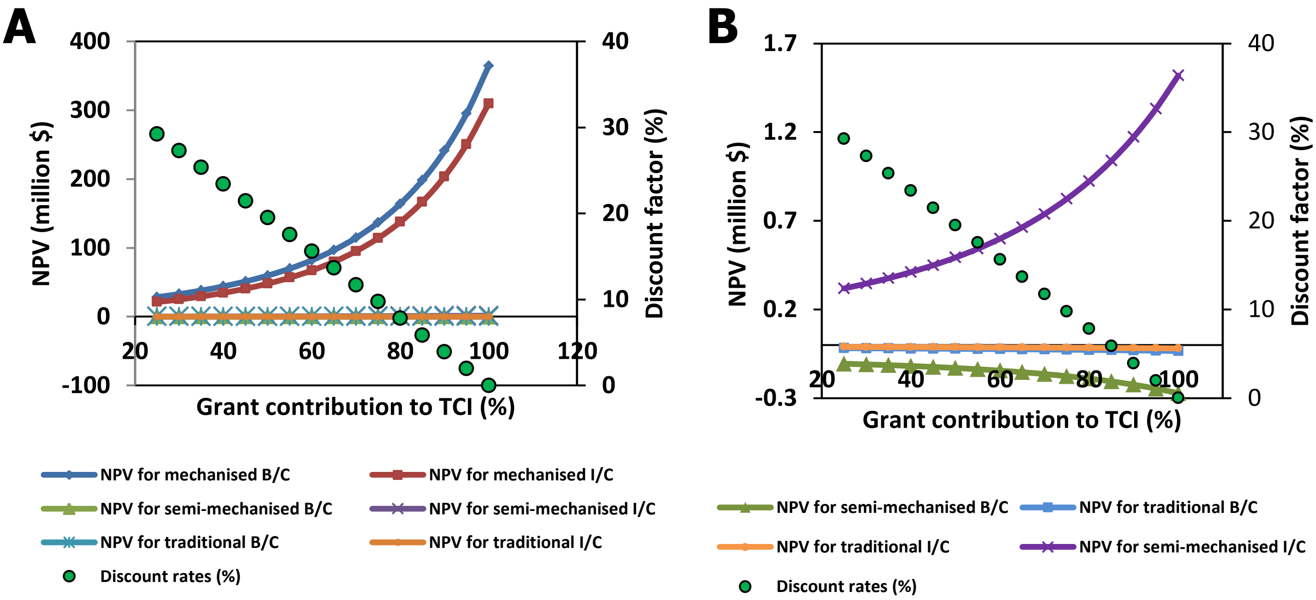


Figure 6-4: Changes in Net Present Value (NPV given in US dollar) to variations in grant-equity financing schemes for selected approaches (mechanisation levels and process energy sourcing) of processing crude palm oil as modelled. Insert A shows NPV changes to grant contributions for all mechanised levels. Insert B is an expansion of NPV changes to grant contributions for only the traditional and semi-mechanised processes for better readability of the data points in insert A.

6.2 Energy and Economic Performance of the Cassava Flour (CF) processes

6.2.1 Energy Performances of the Cassava Flour Processes

The estimated energy intensities for the Cassava flour (CF) processes are presented in Figure 6-5. From the result (Figure 6-5), the energy intensities (energy expended in the CF production process given in MJ/kg CF produced) for the CF processes ranged between 1.96-4.77MJ/kg CF. In addition, the results suggest a consistent trend of decrease in process energy intensity as the level of mechanisation increases (see Figure 6-5). Furthermore, with the exception of the energy intensity of the traditional I/C process, which was higher than that of its corresponding B/C scenario's by 13.4%, a general pattern of equal energy intensities for the B/C and their respective I/C scenarios is noted (see Figure 6-5). This could be attributed to the same process equipment with similar mass conversion and energy efficiencies employed in the B/C and I/C scenarios for the semi-mechanised and mechanised levels. However, the traditional I/C's energy demand was higher than that of the traditional B/C by a margin of 0.64 MJ/kg CF (see Figure 6-5), as a result of the low thermal efficiency (30%) of the maize cobs-fired dryer adopted for cassava chips drying in the wet seasons for the I/C scenario, when compared to the solely direct sun-drying's assumed efficiency of 100% in the B/C scenario. At the B/C level, the energy intensity of the traditional process was higher by 37.6, 44.5 and 52.6% than that of the semi-mechanised, mechanised (grating) and mechanised (Chipping) processes respectively (shown in Figure 6-5). Similarly, at the I/C level, the energy intensity of the traditional process exceeded those of the semi-mechanised, mechanised (grating) and mechanised (Chipping) processes by 46.0, 52.0 and 60.0% respectively (see Figure 6-5). This could be attributed to the combined impacts of variations in the process equipment, energy and mass conversion efficiencies of the process equipment, and process energy forms in the referred food processes (Akinoso *et al*. 2013; Jekayinfa and Bamgboye, 2008).

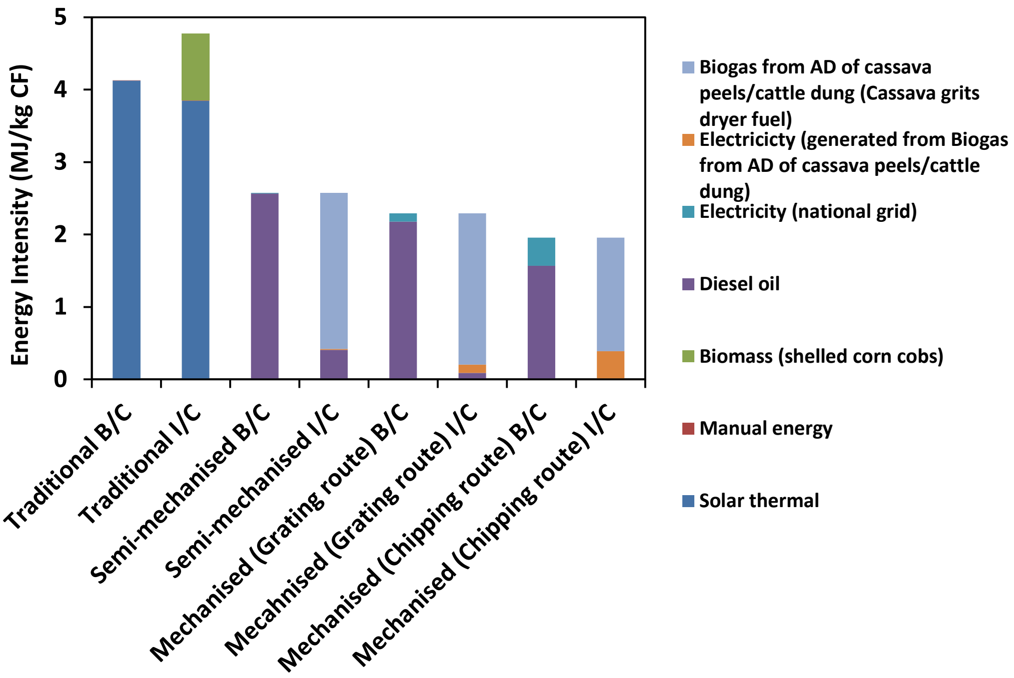


Figure 6-5: Energy demands in the various approaches (mechanisation levels and process energy sourcing) of processing cassava flour as modelled

In the case of energy demands in the alternative mechanised routes (chipping and grating), the chipping route outperformed the grating route with an energy savings of 0.33 MJ/kg (see Figure 6-5). This can be attributed to the elimination of additional unit operations namely the grating, pressing, disintegration and sifting unit operations in the chipping route, which imply elimination of their associated energy demand in the process (see Figure 2-8, section 2.1.1.4). However, the extra unit operations and corresponding higher energy demands in the grating approach is associated with justifiable benefits of assuring product quality and versatility, due to its ability to handle the high cyanide content (>140ppm dry basis) of the bitter cassava variety, and by inference, the sweet variety with less cyanide content (<140ppm dry basis) as well. On the other hand, the simplified chipping approach is restricted to the sweet cassava variety (Dziedzoave *et al.*, 2003).

The energy-mix and their contributions in the CF processes showed solar thermal energy dominated the traditional scenarios with contributions of 99.8 and 80.6% in the B/C and I/C scenarios total process energies respectively (shown in Figure 6-5). Diesel (fossil based) contributed the highest energies in the B/C scenarios of the semi-mechanised, mechanised (grating), and mechanised (chipping) processes with 99.5, 95.0, and 80.0% of the total process energy respectively (see Figure 6-5). On the other hand, the I/C scenarios of the of the semi-mechanised, mechanised (grating), and mechanised (chipping) processes had biomass (biogas from AD of peels/cattle dung used in dryer fuelling and process power) contributing the most to the process energy demands at contributions of 84.2, 96.2 and 100% of the total process energies respectively (see Figure 6-5). The above suggest significant reduction of non-renewable energy demands in the referred B/C processes when compared to their respective I/C scenarios and thus renewable biomass residues (peels) from the process can contribute significantly to the process energy demands.

6.2.2 Economic Performances of the Cassava Flour Processes

6.2.2.1 *Capital Investment for the Cassava Flour Processes*

Figure 6-6 highlights the estimated Total Capital Investments (TCI) and Specific Capital Investments (SCI) (given in $/kg CF produced) for the CF processes as modelled in this study. The noted TCI for the processes ranged between $1147 - $333890 and the SCI between $0.017/kg CF - $0.046/kg CF (see Figure 6-6). In general, a trend of increasing TCI with increasing level of mechanisation can be noted (see Figure 6-6). The noted trend was due to the increase in capacities with increase in the levels of mechanisation considered in the modelling.

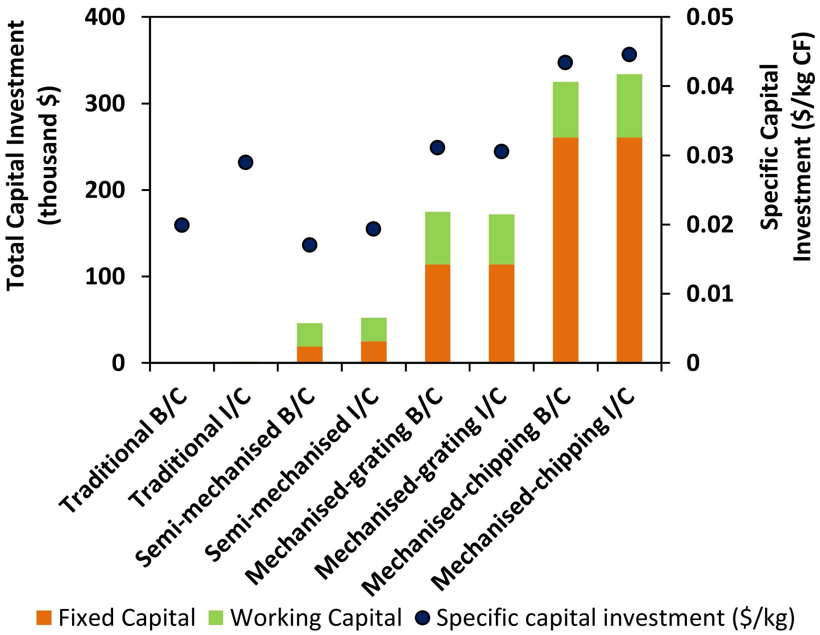


Figure 6-6: Total and Specific Capital Investment for the various approaches (mechanisation levels and process energy sourcing) of processing cassava flour as modelled

At the mechanised level, although the mechanised grating and chipping routes had the same processing capacity of 10 tons fresh cassava/day, a decrease in the TCI for the grating route by 46.2 – 48.6% when compared to that of the chipping route is noted. This could probably be justified by the higher flour recovery rate of 24% for the chipping route technology compared to the 18% recovery rate of the grating route's technology (as presented in Table 3-4, section 3.3). Furthermore, with the exception of the traditional level, a consistent trend of increasing SCI with increase in the level of mechanisation could be noted (see Figure 6-6). The noted trend suggests mechanisation of the CF process could originate in increase in capital investment demands. Comparing the SCI's of the B/C scenarios to their respective I/C scenarios, it can be seen that the SCIs of traditional, semi-mechanised and mechanised-chipping I/C scenarios increased by 31.3%, 12.0% and 2.6% while there was a reduction in the mechanised-grating I/C's by 1.8% (see Figure 6-6). The referred trend indicates in general, the suggested I/C conditions result in increase in capital investment.

6.2.2.2 *Production Cost for the Cassava Flour Processes*

The estimated Total Production Cost (TPC) and Specific Production Cost (SPC) (given in $/kg CF produced) of the modelled CF processes are shown in Figure 6-7. TPC and SPC ranging between of $3015 - $440513 and $0.518/kg CF - $0.675/kg CF respectively were noted for the referred processes (shown in Figure 6-7). Furthermore, with the exception of the mechanised-chipping process, a trend of increasing SPC with increase in the mechanisation level was noticed (Figure 6-7). The result further revealed high SPC ranges of $0.600/kg - $0.675/kg for the semi-mechanised and mechanised-grating processes, and low ranges of $0.518/kg - $0.588/kg for the traditional and mechanised-chipping processes (Figure 6-7). This could be due to the low CF recovery rate of 18% for the grating process path adopted by the semi-mechanised and mechanised-grating levels as compared to the 24% CF recovery rate for the chipping process path which was employed in the traditional and mechanised-chipping levels (Dziedzoave *et al.*, 2003).

In addition, the SPCs of the B/C scenarios when compared to their corresponding I/C's were higher by 0.28, 0.95, 3.61 and 11.94% in the traditional, semi-mechanised, mechanised-grating and -chipping processes respectively (see Figure 6-7). This suggests the increase in the production costs for the traditional and semi-mechanised I/C processes were nominal when compared to those of their respective B/C's, while the increase in cost of production for the mechanised I/C was significant when compared to its B/C's. The latter significance could be attributed to the significant increment in the utility (water and process energy) costs of the mechanised- grating and -chipping I/C scenarios by 25.6 and 50.8% respectively when compared to their respective B/C's (see Figure 6-7).

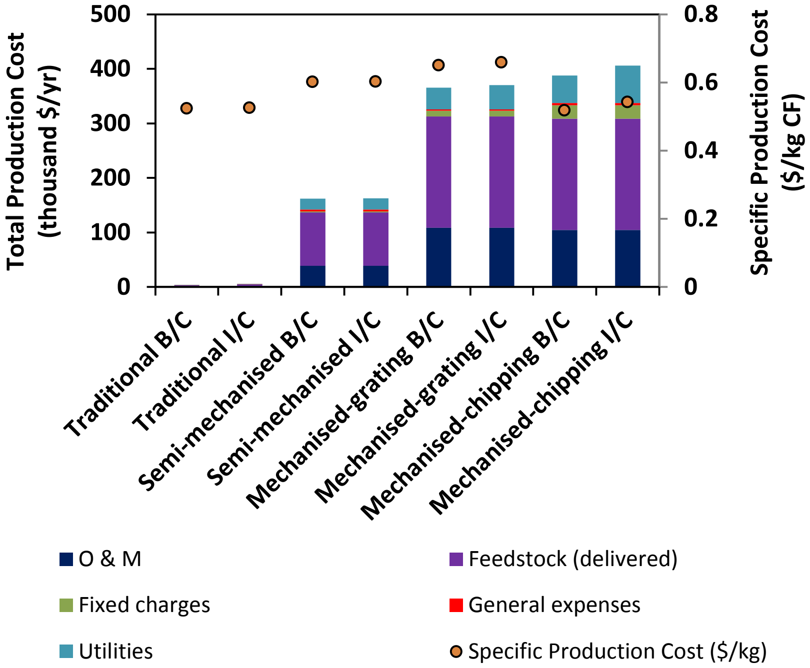


Figure 6-7: Total and Specific Production cost for the various approaches (mechanisation levels and process energy sourcing) of processing cassava flour as modelled

6.2.2.3 *Profitability Assessments of the Cassava Flour Processes*

Table 6-2 summarises the economic results of the private investor financing [60% loan (at an interest rate of 24%) and 40% equity (at an assumed interest rate of 40%), weighted nominal discount rate of 30%] for the CF processes. The results (presented in Table 6-2) suggest at the B/C levels, only the mechanised chipping process was viable (IRR of 36.3%) with regards to the expected IRR of 30%. However, the traditional B/C and mechanised-chipping I/C processes had IRRs of 24% and 24.8% respectively (given in Table 6-2), which shows their promising potential and nearness to being economically viable. Similarly, the I/C levels revealed all the processes were not economically viable in relation to the expected IRR of 30% although the traditional I/C had an IRR of 24% (presented in Table 6-2).

For the expected IRR of 30% to be attained, the selling prices of the CF must be $579/ton, $646/ton, $681/ton and $551/ton for the traditional, semi-mechanised, mechanised-grating and mechanised-chipping B/C processes respectively (given in Table 6-2). On the other hand, for the attainment of the expected IRR of 30%, the flour prices must be $566/ton, $656/ton, $630/ton and $571/ton for the traditional, semi-mechanised, mechanised-grating and mechanised-chipping I/C processes respectively (given in Table 6-2). Thus the traditional B/C and I/C, and mechanised-chipping I/C scenarios' expected CF prices compare well with the prevailing CF price of $560/ton and suggest their nearness to being economically viable.

Table 6-2: Economic results of private investor financing for the cassava flour processing models

Parameters	Traditional		Semi-Mechanised		Mechanised (Grating route)		Mechanised (Chipping route)	
	B/C	I/C	B/C	I/C	B/C	I/C	B/C	I/C
Capacity (tons CF/yr)	6	10	270	270	562	562	562	562
Plant life (yrs)	5	5	10	10	10	10	10	10
Economic evaluations								
NPV ($)	-498	-395	-91618	-107303	-303170	-170380	22870	-43193
IRR (%)	16.3	24.0	-	-	-	-	36.3	24.8
Payback period (yrs)	4	3.4	-	-	-	-	6.5	7.8
Required CF prices for IRR of 30% ($/ton)	579	566	646	656	681	630	551	571

N.B: Economic evaluations considered funding conditions of 60% loan and 40% equity (with a weighted nominal discount rate of 30%)
* B/C – Base-Case scenarios; I/C – Improved-Case Scenarios

Under varying grant-equity funding schemes [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)], it was observed that the semi-mechanised and mechanised-grating processes were still not economically viable, and remained so even under 100% grant funding (shown in Figure 6-8). The traditional B/C and I/C, and the mechanised-chipping I/C processes however achieved NPVs of $22, $60 and $67180 at grant contributions of 60%, 40% and 1% respectively (see Figure 6-8).

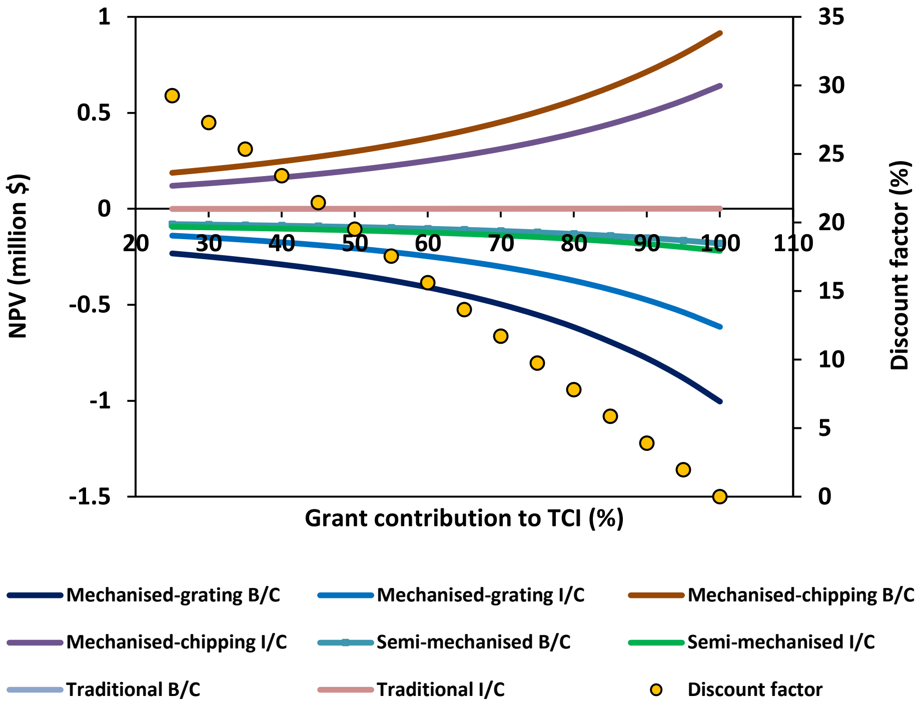


Figure 6-8: Changes in Net Present Value to variations in grant-equity financing schemes for the various approaches (mechanisation levels and process energy sourcing) of processing cassava flour as modelled

6.3 Mass Conversion, Energy and Economic Performances of the modelled Maize Flour (MF) Processes

6.3.1 Mass Conversion and Energy Performances of the Maize Flour Processes

The estimated mass conversion efficiencies of the MF processes as modelled are summarised in Table 6-3. The result (Table 6-3) depicts the traditional process as the most efficient with the highest estimated flour yield of 84.7% as compared to the flour yields of 77.0 and 76.7% for the semi-mechanised and mechanised processes respectively. However, this is due to the inefficient removal of all the components of maize bran (hulls, germs and tip caps) from the flour by the manual sieving in the traditional process. Thus, the basis of the assumed selling price for the flour from the traditional process at three-quarter the price of the equivalent mass value of the semi-mechanised and mechanised flour considered in the economic assessments of the processes (see Appendix B7).

Table 6-3: Estimated mass conversion efficiencies for the maize flour processes

Parameter (%)	Traditional	Semi-Mechanised	Mechanised
Bran per clean grain after sorting	5.3	18	18
Maize flour yield*	84.7	77.0	76.7

*Maize flour yield was determined as: % Flour Yield = (weight of flour/weight of clean grain after sorting) x 100

Figure 6-9 shows the estimated energy intensities (MJ/kg MF produced) for the MF processes considered in this study. The results (Figure 6-9) suggest minimum and maximum energy intensities of 0.17 and 1.48 MJ/kg is required for the maize flour processes as modelled. Comparing the referred range of energy intensity to that of the range of 1.957-4.77 MJ/kg CF for the cassava flour process (see Figure 6-5) suggests the cassava flour (CF) process is the most energy intensive flour process with its minimum required energy even exceeding the maximum of the maize flour (MF) process (Figure 6-9). In the referred processes, the drying unit operation of the CF and MF processes was identified as the most energy intensive unit operation (see details in sections 3.3.2 and 3.3.3). Furthermore, considering cassava has a high moisture content (65 wt% wet basis) as compared to that of maize (24 wt% wet basis), approximately thrice the energy for drying the maize to the required flour moisture (0.1 wt% wet basis) would be needed in drying the cassava to the required flour moisture, thus the main reason for the higher energy demands in the CF processes when compared to the MF processes (Ajiboshin *et al.*, 2011).

Also, there was an increase in the energy demands with increase in the level of mechanisation (as shown in Figure 6-9). The referred trend could be due to the combined impacts of variations in the process equipment, energy and mass conversion efficiencies of the process equipment, and process energy forms in the referred food processes (Akinoso *et al.* 2013; Jekayinfa and Bamgboye, 2008). Furthermore, from the results of the process energy demands ((Figure 6-9), the energy intensities for the I/C scenarios of the semi-mechanised and mechanised levels were higher than their corresponding B/C scenario's by 0.01 and 0.12 MJ/kg respectively, while the energy intensity of the traditional B/C scenario was higher than the corresponding I/C scenario's by of 0.01 MJ/kg. In the models of the semi-mechanised and mechanised I/C processes, maize cobs replaced solar (thermal) drying and diesel as dryer fuel respectively (see details in section 3.2.3.1). Generally, biomass-fired dryers are noted to have low energy efficiencies when compared to that of same capacity diesel-fired dryers or sun-dryers due to thermal energy utilisation in evaporating the moisture in the biomass fuel during the combustion process (Bahadori *et al.*, 2014).

Therefore, more maize cobs (biomass fuel) were required to perform the same drying duties in the I/C scenarios hence the reason for the noted increasing energy intensity in the referred I/C scenarios when compared to the energy intensities of their corresponding B/C scenarios.

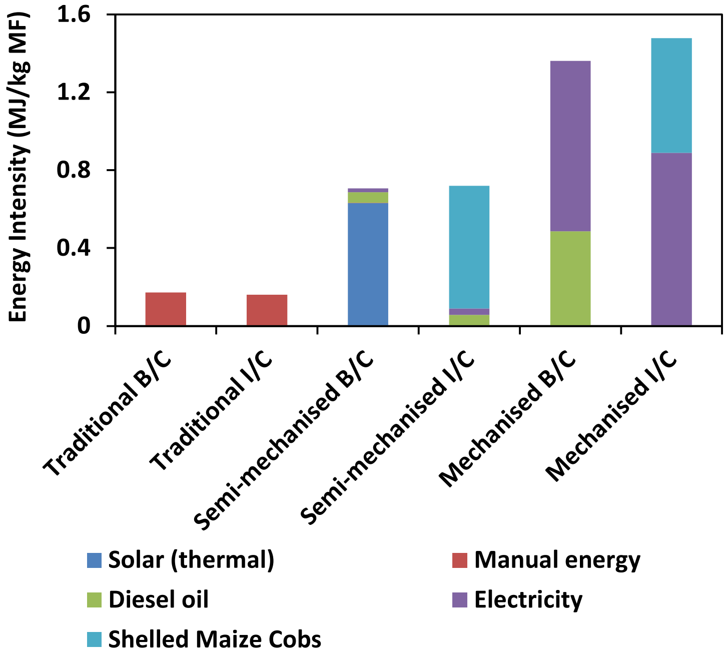


Figure 6-9: Energy demands in the various approaches (mechanisation levels and process energy sourcing) of processing maize flour

The energy forms and contributions in the traditional, semi-mechanised and mechanised MF processes revealed manual energy dominated the energy mix of the traditional processes with contribution of 99.99% to the total energy demands for the B/C and I/C scenarios (as shown in Figure 6-9). On the other hand, at the semi-mechanised level, solar thermal (as drying energy) dominated the B/C scenario with a contribution of 89.2% of the total process energy while maize cobs (dryer fuel) was the principal energy in the I/C scenario with a contribution of 87.5% of its process energy (see Figure 6-9) Thus, the referred trends suggest the drying unit operation as the most energy intensive unit in both the B/C and I/C maize flour processes. Furthermore, modern energies (diesel and electricity) were required in only the semi-mechanised and mechanised levels with electricity and diesel contributions ranging 2.8-4.6% and 7.7-7.8% of the total process energy for the semi-mechanised process and 60.2-64.3% and 35.7-39.8% of the total process energy for the mechanised process respectively (see Figure 6-9). The noted trend thus suggests an increase in the level of mechanisation in the MF process results in an increase in modern energy demand.

6.3.2 Economic Performances of the Maize Flour (MF) Processes

6.3.2.1 *Capital Investment for the Maize Flour Processes*

The Total Capital Investment (TCI) and Specific Capital Investment (SCI) (given in $/kg MF produced) for the MF processes (shown in Figure 6-10) ranged between $484-262852 and $0.012-0.070/kg respectively. It was noted that the TCI increased with increase in the level of process mechanisation which was due to the corresponding increase in capacities considered in the models (see Figure 6-10). Furthermore, the traditional process attained the highest SCI ranging between $0.062-0.070/kg MF while the mechanised I/C process recorded the least of $0.012/kg MF (see Figure 6-10) suggesting a general trend of decrease in SCI with increase in the level of mechanisation which could be attributed to the benefits of economies of scale in the process.

Additionally, comparing the SCI for the I/C scenarios of each mechanisation level to the SCI of their respective B/C revealed the SCI for the traditional I/C process was higher by 21.6% while the SCI for the I/C scenarios of the semi-mechanised and mechanised processes decreased by 12.0% and 30.0% respectively (see Figure 6-10). The noted trend for the traditional process was mainly due to the relatively high investment cost of $150 for the improved metal silo (considered for grain storage in the I/C scenario) as compared to the $20 for the traditional silo (considered for maize cobs storage in the B/C scenario), although this could probably be justified by the significant decrease in grain storage losses by 84% in the improved metal silo when compared to the latter (De Groot, 2013). On the other hand, the noted trend of decrease in SCI in the semi-mechanised and mechanised I/C processes when compared to the SCI of their respective B/C scenarios was mainly due to the considered farm gate maize prices of $170/ton and maize prices of $398.2/ton from licensed buying companies (LBC) for the I/C and B/C scenarios respectively (see details in Appendix B7). The referred sourcing of feedstock and its associated cost resulted in a decrease of 15.7% and 42.5% in the working capitals for the I/C scenarios of the semi-mechanised and mechanised processes when compared to the working capitals of their respective B/C's (see Figure 6-10).

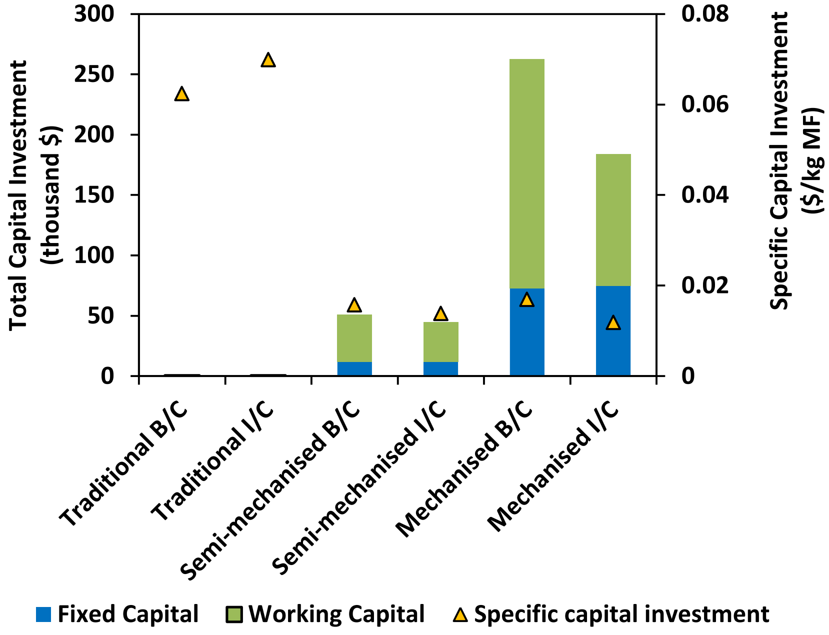


Figure 6-10: Total and Specific Capital Investment for the various approaches (mechanisation levels and process energy sourcing) of processing maize flour as modelled

6.3.2.2 *Production Cost for the Maize Flour Processes*

Figure 6-11 summarises the Total Production Cost (TPC) and Specific Production Costs (SPC) (given in $/kg MF produced) of the MF processes. From the result, it was noted that TPC and SPC for the MF processes ranged between $1269-$1140400 and $0.423/kg MF-$0.817/kg MF respectively (see Figure 6-11). Furthermore, a general trend of decrease in the SPC as the level of mechanisation in the process increases was noted (see Figure 6-11). The SPC for the traditional B/C process was higher than the SPC for the semi-mechanised B/C and mechanised B/C processes by 11.7 and 10% respectively (see Figure 6-11). Similarly, the SCI for the traditional I/C process was higher than those for the semi-mechanised I/C and mechanised I/C scenarios by 16.5% and 41.9%. The referred trends suggest mechanisation of the MF process contributes to savings in production cost with the savings being proportional to the level (extent) of mechanisation.

On the other hand, there was a reduction in the SPC of the traditional, semi-mechanised and mechanised I/C scenarios by 10.9, 15.7 and 42.5% respectively when compared to the SPC of their respective B/C scenarios. The trend in the semi-mechanised and mechanised processes could be attributed to the same reason (feedstock cost factor) given above for the similar trends under the SCI evaluations (given in section 6.3.2.1). The noted trend for the traditional process could be attributed to the significant savings in the grain losses in the I/C scenario (as indicated in section 6.3.2.1) which resulted in an increase in its MF production capacity by 12.1% when compared to the production capacity of the B/C scenario.

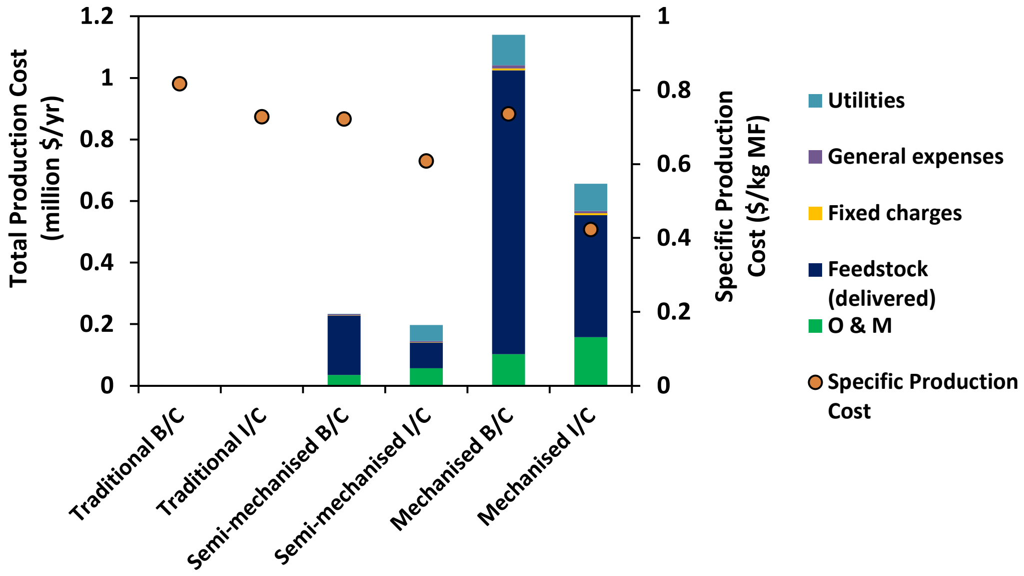


Figure 6-11: Total and Specific Production cost for the various approaches (mechanisation levels and process energy sourcing) of processing maize flour as modelled

6.3.2.3 *Profitability Assessments of the Maize Flour Processes*

The economic results for the private investor financing ([60% loan (at an interest rate of 24%) and 40% equity (at an assumed interest rate of 40%), weighted nominal discount rate of 30%]) of the MF processes are summarised in Table 6-4. The results (given in Table 6-4) revealed all the Base-Case (B/C) scenarios for the MF processes as modelled were not economically viable for an expected IRR of 30%. On the other hand, the semi-mechanised I/C and mechanised I/C process scenarios showed an improvement in the economic performance with IRRs of 18.8% and 132.8% respectively (see Table 6-4). However, considering an IRR of 30% was expected for viability of the processes, the semi-mechanised I/C process did not suffice, suggesting the mechanised I/C process as the only viable option. Furthermore, the required MF prices for the attainment of the IRR of 30% (presented in Table 6-4) show the nearness of the various processes to being viable when compared to the present MF price at $560/ton.

Table 6-4: Economic results for Private investor financing of the maize flour processing models

Parameters	Traditional		Semi-Mechanised		Mechanised	
	B/C	I/C	B/C	I/C	B/C	I/C
Production Capacity[1]	1.6	1.8	227.3	324.3	1551.3	1551.3
Plant life[2]	5	5	10	10	10	10
Economic evaluations						
NPV (thousand $)	-1.94	-1.85	-18.45	-13.54	-1035.85	746.36
IRR (%)	-	-	-	18.8	-	132.8
Payback period[2]	-	-	-	3.4	-	0.5
Required MF prices for IRR of 30% ($/ton)	904.5	828	689	578	-	426

N.B: Economic evaluations considered funding conditions of 60% loan and 40% equity (with a weighted nominal discount rate of 30%); [1]expressed in tonnes of MF/year; [2]given in years.
B/C – Base-Case scenarios; I/C – Improved-Case Scenarios

The improvement in the economic performances of the semi-mechanised and mechanised I/C processes were mainly due to their lower SPC as compared to those of their B/C scenarios which could be traced to their feedstock sources and cost (as indicated in section 6.3.2.2). In the semi-mechanised I/C scenario, the feedstock and its mobilising labour cost from farm gates resulted in annual savings of $91189.4 when compared to the purchasing of feedstock from LBCs in the semi-mechanised B/C scenario (see Appendix B7). Introduction of the maize cobs as dryer fuel increased its annual production cost by 26% (which corresponds to the cost of labour and transportation of the cobs to the MF processing facility) as compared to the solar (thermal) drying energy which was available at no cost in the B/C scenario (see Appendix B7). Although cob residues as dryer fuel increased the production cost by 26%, it ensured extension of operation to wet seasons, with corresponding increase in annual production capacity by 30%, which contributed to the semi-mechanised I/C process becoming economically promising (IRR of 18%). Thus the economic viability of the semi-mechanised process is highly reliant on the feedstock cost and reliability of the drying energy (translating to increase annual production capacity), and to a lesser extent on the drying energy cost.

On the other hand, the mechanised MF process purchasing of the feedstock from farm gates in the I/C scenario resulted in annual savings of $480029.12 when compared to the B/C scenario's feedstock supply from LBCs. In the energy integration schemes, the consideration of maize cobs-fired dryers in the I/C scenario replacing the diesel fired dryers (considered in the B/C scenario) resulted in total annual savings of $11368.56 (see details in Appendix B7).

Therefore the savings in feedstock cost and dryer energy cost contributed 97.7 and 2.3% respectively to the high improvement in the economic performance of the mechanised I/C process. Hence implementation of mechanisation in MF processes requires low feedstock costs in addition to reliable and cheaper drying energy to be economically viable.

Figure 6-12 shows the economic performances of the MF processes under different grant-equity funding schemes [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)]. It was noted that the traditional processes (B/C and I/C), semi-mechanised and mechanised B/C processes remained unviable with negative NPVs under even 100% grant funding (see Figure 6-12). On the other hand, the economic performance of the semi-mechanised I/C process improved with a positive NPV of $1422 obtained at 40% grant - 60% equity funding scheme, thus suggesting the semi-mechanised I/C process could suffice under grant funding.

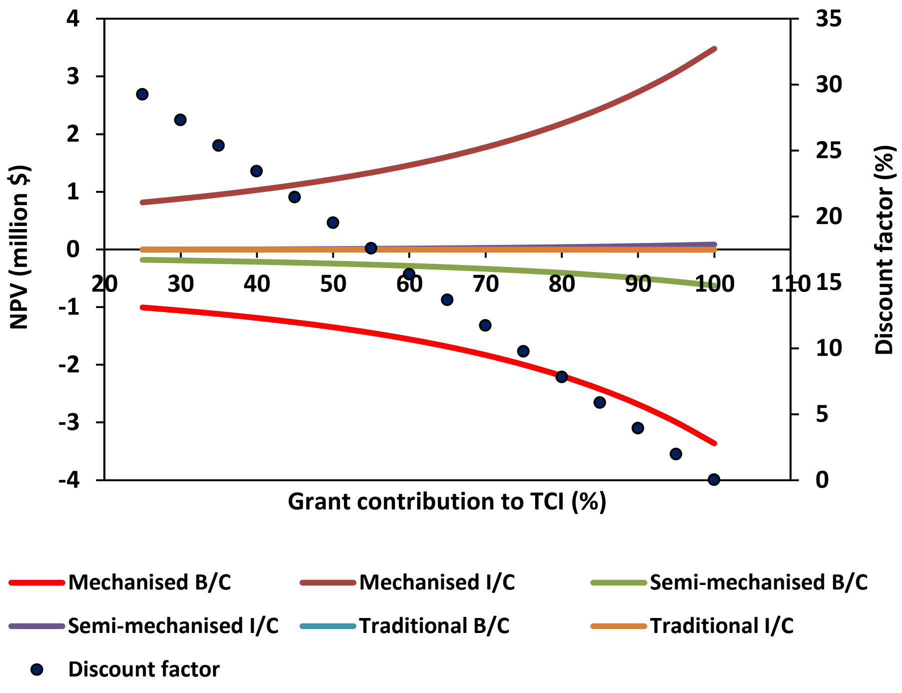


Figure 6-12: Changes in Net Present Value to variations in grant-equity financing schemes for the various approaches (mechanisation levels and process energy sourcing) of processing maize flour as modelled

7 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to investigate the economic impacts of mechanisation and strategic in-house energy generation from process residues in crude palm oil (CPO), cassava flour (CF) and maize flour (MF) processing. This was achieved through developing theoretical process and economic models for the referred food processes. For each food process, traditional, semi-mechanised and mechanised processes (based on the level or extent of mechanisation in the process) were considered. Two scenarios were modelled for each level: Base-Case (B/C) scenarios entailing current processing approaches with conventional process energy-mix and corresponding suggested Improved-Case (I/C) scenarios which entailed potential process energy generation from the process biomass residues (in-house bioenergy generation and integration).

The process modelling of advanced in-house energy processes were developed in Aspen Plus® simulation software. All economic models were based on 2014 economic conditions of Ghana. The economic models considered private investor funding [60% loan (at an interest rate of 24%) and 40% equity (at an assumed interest rate of 40%), weighted nominal discount rate of 30%]. Thus, an assumed IRR of 30% was considered ideal for the economic viability of the processes. Sensitivity analysis was also undertaken to assess impacts of grants funding [i.e. part grant (discount rate of 0%) and the remaining investment cost from equity (discount rate of 40%)] on the profitability of the processes. Below are conclusions and recommendations reached based on the results of the study.

7.1 Conclusions on the Modelled Food Processes

7.1.1 CPO Processes

At the B/C, the semi-mechanised process was found to be the most energy intensive process (37 MJ/kg CPO), followed by the traditional (28 MJ/kg CPO) and the mechanised (6 MJ/kg CPO). Similar trends were observed for the I/C scenarios; the semi-mechanised, traditional and mechanised processes' energy intensities were 12, 11 and 6 MJ/kg respectively. The above trend was due to combined impacts of variations in the process equipment, energy efficiencies and mass yields of the process equipment, and process energy forms (Akinoso et al. 2013; Jekayinfa and Bamgboye, 2008). Hence, increase in the level of mechanisation of the CPO process is not necessarily associated with an increase in energy savings as the energy demands of the traditional process were lower than that of the semi-mechanised processes.

It was showed that the semi-mechanised I/C, mechanised B/C, and mechanised I/C scenarios (as modelled) were the economically viable options under the baseline economic conditions with IRR of 143, 47 and 40% respectively. Hence mechanisation of the CPO process, which increases production capacity and improves mass yields, seems to be economically beneficial. A sensitivity analysis further revealed the traditional B/C, traditional I/C and semi-mechanised B/C scenarios were not viable under conditions of 100% grant funding. The above observations suggest that, the poor economic performance of the traditional B/C, traditional I/C and semi-mechanised B/C processes is undoubtedly a consequence of the impacts of their high production costs ranging between $0.431–1.187/kg, which is not justified by the CPO price of $0.71/kg CPO. Additionally, their high production costs seem to rely on the combined effect of the process energy demands and mechanisation, and to a less extent on the feedstock cost. For example, for this specific food process, the contribution of the feedstock on the TPC varied between 42 and 60% for all the levels of mechanisation, whilst the referred contribution of feedstock in the case of MF was between 30 and 80%. Under assumptions of similar effects of mechanisation (semi-mechanised B/C and I/C level), an improvement of 15% of energy efficiency is realised by replacing inefficient tripod stove with improved cook stoves, and as a result the I/C process attained economic viability (IRR of 143%). Therefore, mechanisation of the CPO process is economically viable, but when implemented together with improvement in the energy efficiency of the process.

7.1.2 CF Processes

For the B/C scenarios, the process energy demand of the traditional process was higher by 37.6, 44.5 and 52.6% than those of the semi-mechanised, mechanised-grating and mechanised-Chipping processes respectively. Likewise, the energy demands of the traditional I/C process exceeded those of the semi-mechanised, mechanised-grating and mechanised-chipping I/C processes by 46.0, 52.0 and 60.0% respectively. The combined effects of differences in mass yields and energy efficiencies of the process equipment, as well as energy forms was the main reason for the trend stated above (Akinoso et al. 2013; Jekayinfa and Bamgboye, 2008).

The economic assessment (for the private investor financing) revealed that the mechanised-chipping process was the only viable option (IRR of 36%), considering the expected IRR of 30% for economic viability. However, the traditional B/C, traditional I/C and mechanised-chipping I/C processes had appreciable IRRs of 16.3%, 24.0% and 24.8% respectively, which show their nearness to being economically viable. Sensitivity analysis showed the semi-mechanised and mechanised-grating processes remained uneconomical under 100% grant funding while the traditional B/C, traditional I/C and mechanised-chipping I/C processes sufficed with positive NPVs of \$22, \$60 and \$67180 at grant contributions of 60%, 40% and 1% of the TCI respectively (the remaining funds sourced as equity), which portrays their prospective viability under higher grant supports. Hence, interest rate on loans is suspected to be the determining factor for economic viability of the referred processes. Interventions in the traditional I/C process, such as employing maize cobs as dryer fuel, which contributes to reduction in wood fuel detriments such as deforestation, and improvement in the IRR to 24%, suggest the referred process could suffice under policies and funding conditions of Development Financing Institutions (DFI's) with objectives of improving socio-economic and environmental conditions.

Mechanisation has a substantial positive impact on energy demand in the CF process, which is reflected in energy savings of up to 60% of the required energy for traditional operations. Additionally, a comparison between different levels of mechanised processes (semi- and mechanised) suggests that the energy source, which determines the energy cost, turns out to be more important than their energy intensities regarding economic viability of the processes. For instance, replacing the grid power (\$0.21/kWh) with the relatively costly bioelectricity from AD of peels/cattle dung (\$0.43/kWh) in the mechanised-chipping process resulted in the referred process to become unviable. In conclusion, mechanisation is definitely a way to improve the economics of the CF processes. Major governmental efforts, such as tax exemptions and provisions of soft loans, must however be considered to make bioenergy a cheap source of process energy to replace the unreliable traditional diesel and grid electricity, when mechanisation is implemented.

7.1.3 MF Process

The process energy estimates for the modelled B/C scenarios of the MF processes showed that, the energy demands for the mechanised process was higher by 87.3 and 48.0% when compared to those of the traditional and semi-mechanised processes respectively. Similarly for the I/C scenarios, the energy demands for the mechanised process exceeded those of the traditional and semi-mechanised processes by 89.1 and 51.2% respectively. This trend was as a result of the collective influences of variations in the process energy forms and equipment, and energy and mass conversion efficiencies of the process equipment (Akinoso *et al*. 2013; Jekayinfa and Bamgboye, 2008). Thus, an increase in the level of mechanisation results in corresponding increase in the process energy demands.

The baseline economic models revealed all the B/C scenarios were not economically viable and attained negative NPV ranging from -$1935- to -$1035850. Under the I/C scenarios, the traditional process remained unviable with an NPV of -$1854. However, the economics improved for the semi-mechanised and mechanised processes, which attained IRR of 19 and 133% respectively, suggesting the mechanised I/C process as the only economically viable option with regards to the expected IRR of 30%.

At the same farm gate prices for the feedstock, the traditional, semi-mechanised and mechanised I/C processes were economically unviable, promising and viable respectively. Also, at a high contribution of feedstock on the TPC for the mechanised I/C process (60% of the TPC, see Figure 6-11), the impact of mechanisation on the economics was manifested as the process attained an IRR of 133%. Thus, mechanisation of the process provides an avenue for reduction of the effect of feedstock price on the process economics. However, if the effect of mechanisation is not considered, a high impact of feedstock cost on economic viability of the processes is demonstrated. For instance, feedstock at farm gate prices ($170/tonne shelled maize) contributed to the semi-mechanised and mechanised processes to be economically promising (IRR of 19%) and viable (IRR of 133%) respectively, while feedstock at LBC prices ($398/tonne shelled maize) resulted in both processes to be economically unviable. The important effect of feedstock on process' economy was not only observed for MF (between 30 and 80%), the feedstock contribution to the TPCs of the other two studied food processes (CPO and CF) was as high as 60% of their TPCs (see Figure 6-3 and Figure 6-7).

The use of cob residues as dryer fuel to replace sun-drying (limited to dry season of 7 months per year) in the semi-mechanised process increased the production cost by 26% due to the higher cost of cobs at $0.01/MJ, as compared to sun-drying at no cost. Reliability in operation of the process is however ensured by replacing sun-drying with cobs as dryer fuel. Hence the operational period could be extended up to 10 months per year and consequently an increase in annual production capacity by 30%, which contributed to the process becoming economically promising (IRR of 18%). On the other hand, the traditional B/C and I/C, and semi-mechanised B/C processes, whose drying operations were solely by sun-drying (at no cost), were observed to be economically unviable. Hence, the cost of the drying energy appears not to be a major determining factor for the economic viability of the MF process. Thus, the economics of the MF process is directly related to the reliability of the energy source, translating to increase in annual operations and capacity, rather than the drying energy cost. In conclusion, combination of mechanisation, lower feedstock prices (around farm gate prices) and use of reliable and cheaper energy sources is necessary for economic viability of the MF process. Although feedstock prices highly impact the MF process economics, coupling mechanisation with a reliable source of energy minimises the impact of feedstock price on the economics.

7.1.4 Overall Conclusions on Food Processes

In general, increasing the level of mechanisation in the studied food processes leads to increase in the modern energy (electricity and diesel) demand. At the highest level of mechanisation, the prevalent modern energy varies for each food process; electricity for CPO, diesel for CF and diesel/electricity for MF. Thus, the studied food processes are all exposed to high risk regarding operation due to their dependence on modern energy. Irregularities in electricity supply and high fluctuations in diesel fuel prices (IEA, 2014), denoting low reliability of electricity and crude diesel in SSA, implies uncertainties in the economics of the mechanised food processes. Therefore CPO's challenge is basically ensuring steady production at highly unreliable conditions of the grid power. Alike CPO, maize flour process also face similar challenges regarding reliability of grid electricity though other challenges such as uncertainty as a result of volatility in diesel prices in the region makes the process highly vulnerable regarding economic viability. On the other hand, the economics of the CF process is largely susceptible to the high instability of the diesel price. In this adverse scenario of reliability of modern energies, improvement in the coverage and reliability of electricity supply (uninterrupted service year round) and stringent policies and regulations for pricing diesel fuel must be implemented to realise the economic benefits associated with the mechanised processes.

Process biomass residues have potential to replace conventional energy in the studied food processes. Different potential contributions of residues to process energy are observed for the processes. CPO process has the highest potential for biomass residue uses as energy at all levels of mechanisation; contribution of solid residues (mesocarp fibre, empty fruit bunch and palm kernel shells) to process energy ranged between 99.4 and 100%. Also high potential for the CF processes is observed; cassava peels residues enabled (although required cattle dung for feasibility) the process to meet 84.2-100% of its energy. The lowest residue to process energy potential is observed for MF where cobs residues meet only 39.8-87.5% of the process energy. The lowest potential found for MF is explained by the fact that other types of energy such as diesel are required to operate other steps of the process (e.g. shelling), which cannot be met by the cobs residues. Thus the use of biomass residues for bioenergy must be promoted to realise its potential in the mechanised food processes.

Mechanisation is economically beneficial (realising economic viability) only at the highest mechanised level for CPO and CF processes. For the MF process, mechanisation on its own is not beneficial; economic viability is realised only by coupling the highest level of mechanisation with bioenergy integration (cobs residue as dryer fuel). The approach of bioenergy integration (from residues) shows economic benefits for the CPO process at the semi- and mechanised levels, whilst no economic viability is realised for the CF process at all the levels of mechanisation. In conclusion, implementing mechanisation in food processing is essential to realise economic viability under the regional economic influences. Caution must however be exercised when mechanising MF processes as economic viability is also associated to the energy integration schemes. Hence, cobs residues represent a much better source of drying energy, with derived economic benefits, than the traditional diesel.

7.2 Conclusions on Renewable Energy Generation from Food Process Residues

In the Ghanaian context, the bioelectricity feed-in-tariff (FIT) of \$0.396/kWh (PURC, 2013) is 13.8% higher than the customary maximum grid power price of \$0.348/kWh. However, adverse economic and governmental policies for investment in the region, demonstrated by the high tax rate (25% of net income) and interest rate of local banks (24%), and desires in short term loans with high returns by local banks, make commercial bioenergy from food processing residues economically unviable in Ghana. Hence, the vast economic challenges outweigh the existing incentive of FIT (Daniel *et al.*, 2014). Therefore, reforms in governmental policies such as duty free importation of bioenergy technologies, tax exemptions for bioenergy industries, provision of soft loan or grant funding by government or Development Finance Institutions (such as UNEP's Renewable Energy Enterprise Development (REED) program, and African Development Bank) is necessary to realise the bioenergy potentials in Ghana. Nevertheless, the following specific bioenergy outlines from this study are worth considering irrespective of the aforementioned economic limitations:

- A scenario of a 13 ton FFB/hr CPO mill operator undertaking an anaerobic digestion (AD) of palm oil mill effluent (POME) project for purposes of in-house energy generation via gas-engine route, under funding conditions of 60% loan (interest rate of 24%) and 40% equity from the mill operator (interest rate of 0%), is economically promising. Under such scheme, an expected minimum CPO mill's power price of $0.337/kWh (assuming all surplus power is sold at the grid price of $0.348/kWh) results in profitability of the CPO process with an IRR of 44.1% (for an expected IRR of 30% by the CPO mill).
- Modification of the current approach of in-house energy generation from solid residues in CPO mills, by shredding and drying the efb residue's moisture content to 45 wt%, for use as additional boiler fuel, improves the economics of the in-house bioenergy process with a margin of 1.3–3.0% increase in IRR. Furthermore, under funding conditions of 60% loan (interest rate of 24%) and 40% equity from the mill operator (interest rate of 0%), the expected power price of $0.679/kWh (assuming all surplus power is sold at the grid price of $0.348/kWh) still gives an appreciable profit margin with an IRR of 41.7% attainment by the CPO mill (for an expected CPO mill's IRR of 30%). Hence, the referred approach is worth considering for implementation as it ensures energy security for the CPO milling process in addition to appreciable profit gains.
- A 4.8 and 10 tons fresh cassava/day CF mill operator undertaking an AD of peels/cattle dung to in-house power/dryer fuel (biogas), under an investment scheme of 60% loan (interest rate of 24%) and 40% equity from the mill operator (interest rate of 0%), could provide power to the CF mill at no cost if all excess generated power is sold at the grid price of $0.348/kWh. The above scheme could result in the CF mills attaining IRRs of 42.8-96.3% (for an expected IRR of 30% for the CF mill). Thus, the CF mill operator could consider such in-house energy scheme, particularly for the purpose of ensuring energy availability for regular operation of the mill, considering the trending intermittent supply of grid power or unavailability of electric power in such CF processing settings.

7.3 Recommendations

The study presents potentials and economic impacts of mechanisation and in-house energy provision from food processing residues, which offers groundwork for further improvement for the objective of this study, as well as possible extension of the concepts to other industries such as sawmills and farms among others. It is therefore important to address the following gaps and possible variables that affected the findings in the study:

- Given the process models were based on various assumptions and related literature, some of which are out of the African context due to lack of adequate literature, it is recommended that the models should be improved with experimental data generated for the identified technologies, to provide a more representative scenario in the African context. Particularly, the adapted study on AD of cassava peels/cattle dung (Adelekan, 2012) had a primary objective of identifying ideal mixing ratios of substrates, but not the optimum conditions for maximum biogas yield. This may account for the low biogas yield of 21.3 l/kg-TS (for 1:1 ratio of cassava peels/cattle dung), as compared to expected yield of 600-650 l/kg-TS for AD of only cassava peels under optimum conditions (Cuzin et al, 1992; Jekayinfa and Scholz, 2013; Panichnumsin et al, 2010). Thus, the AD process modelling was based on biogas yield estimate from optimised AD processes of cassava peels and cassava pulp/pig manure (Cuzin et al, 1992; Jekayinfa and Scholz, 2013; Panichnumsin et al, 2010). Hence, experimental investigations on the optimum process conditions for the cassava peel/cattle dung substrate should be carried out to for refinement of the process/economic models of the AD to electric power process.
- The proposed FIT at 13.8% higher than the maximum power price of $0.348/kWh is still less than suggested 20% margin by Leibbrandt (2010), and not motivating enough considering the financial challenges encountered in implementing such bioenergy projects. Therefore, Life cycle assessment (LCA) on the bioenergy processes should be investigated to ensure their true environmental benefits are reflected in their appraisal. The findings should then be considered in upgrading the feed-in-tariff (FIT) for bioelectricity.

REFERENCES

Abdullah, N., Sulaiman, F., and Gerhauser, H. (2011). "Characterisation of Oil Palm Empty Fruit Bunches for Fuel Application." Journal of Physical Science, Vol. 22(1), 1–24.

ACET - African Center for Economic Transformation, (2013). "Pathways to Transformation: The Oil Palm Value Capture Opportunity in Africa." Retrieved on 8th August, 2014 from: http://acetforafrica.org/wp-content/uploads/2013/09/130806LongPalm.pdf

Adelekan, B.A and Bamgboye, A.I (2009). "Comparison of biogas productivity of cassava peels mixed in selected ratios with major livestock waste types." African Journal of Agricultural Research: 4 (7), 571-577.

Adelekan, B.A. (2012). "Cassava as a Potent Energy Crop for the Production of Ethanol and Methane in Tropical Countries." Int. J. of Thermal & Environmental Engineering Volume 4, No. 1, 25-32.

Adeniyan , O. N., Aluko, O. A., Olanipekun, S. O., Olasoji, J. O. and Aduramigba-Modupe,V. O. (2014). "Growth and Yield Performance of Cassava/Maize Intercrop Under Different Plant Population Density of Maize." Journal of Agricultural Science; Vol. 6, No. 8.

Adjei-Nsiah, S., Zu, A.K.S. and Nimoh, F. (2012). " Technological and Financial Assessment of Small Scale Palm Oil Production in Kwaebibrem District, Ghana." Journal of Agricultural Science: 4(7), 111-120.

AFREPREN (2002). "Renewable Energy Technologies in Africa. An Energy Training Course Handbook." Nairobi: AFREPREN/FWD, AFREPREN Occasional Paper: 10.

Afrique Avenir (2010). [ONLINE] Available at: http://www.afriqueavenir.org/en/2010/09/14/wind-farms-are-multiplying-onthe-african-continent/ [Accessed 5 November 2015].

Ajao, K.R, Ajimotokan, H.A., and Olaomi, J. (2009). "Development and Performance Evaluation of a Groundnut oil Expelling Machine." New York Science Journal, 2(6), 76 – 79.

Ajiboshin, I.O., Omotade, S.A., Sadiq, A.O., Yussuf, I.G., Oyelola, O.T., Raheem, S., Bello, R.A., Adesina, A.O., and Adedeji, W.O. (2011). "Energy requirement and cost of drying cassava flour." African Crop Science Conference Proceedings, Vol. 10. pp. 441 – 444.

Ajoku, K.B. (2012). "Modern use of solid biomass in Africa: prospect for utilization of agro-waste resources in Nigeria." In: Rainer Janssen, Dominik Rutz (Eds.), Bioenergy for Sustainable Development in Africa. Springer, Netherland, ISBN 978-94-007-2180-7, pp. 131–146.

Akingbala, J. O., Oyewole, O. B., Uzo-Peters, P. I., Karim, R. O., and Bacuss-Taylor, G. S. H. (2005). "Evaluating stored cassava quality in gari production". Journal of Food, Agriculture and Environment: 3, 75-80.

Akinoso, R., Olapade, A.A., and Akande, A.A. (2013). "Estimation of Energy Requirements in Cowpea Flour Production in Nigeria." Focusing on Modern Food Industry (FMFI), Volume 2 Issue 2, May.

Al Seadi, T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S. and Janssen, R. (2008). In: Al Seadi, T. (Ed.), "Biogas Handbook", Published by University of Southern Denmark Esbjerg, Denmark, ISBN 978-87-992962-0-0.

Alazraque-Cherni, J. (2008). "Renewable energy for rural sustainability in developing countries." Bulletin of Science, Technology & Society, 28(2), 105-114.

Angelonidi, E., and Smith, S. R. (2013). "A Critical Assessment of Wet and Dry Anaerobic Digestion Processes for the Treatment of Municipal Solid Waste and Food Waste." Doctoral dissertation, Imperial College London.

Arami-Niya, A., Daud, W.M.A.W., and Mjalli, F.S. (2010). "Using granular activated carbon prepared from oil palm shell by $ZnCl_2$ and physical activation for methane adsorption." J. Anal. Appl. Pyrolysis 89, 197-203.

ARE- Alliance for Rural Electrification, (2011). [ONLINE] Available at: http://www.ruralelec.org/ [Accessed 10 December 2013].

Arvizu, D., Balaya, P., Cabeza, L., Hollands, T., Jager-Waldau, A., Kondo, M., Konseibo, C., Meleshko, V., Stein, W., Tamaura, Y., Xu, H. and Zilles, R. (2011). "Direct Solar Energy." In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ata, J.K.B.A. (1974). "Processing and quality characteristics of Ghanaian commercial palm oils." Ghana Jnl agric. Sci: 7, 147-149.

Aworh, O. C. (1993). "Exploration and exploitation of indigenous technology for the growth of the food and beverage industries: an overview." Proceedings of 17th Annual Conference of the Nigerian Institute of Food Science and Technology, Ilorin, Dec 6-10; Akingbala, J. O., Ed.; NIFST: Lagos, Nigeria, 1993, 20-37.

Aworh, O.C. (2008). "The role of traditional food processing technologies in national development: the West African Experience." In: Robertson GI, Lupine JR (eds) Using food science and technology to improve nutrition and promote national development, chapter 3. International Union of Food Science and Technology, Canada.

Bahadori, A., Zahedi, G., Zendehboudi, S. and Jamili, A. (2014). "Estimation of the effect of biomass moisture content on the direct combustion of sugarcane bagasse in boilers." International Journal of Sustainable Energy, 33:2, 349-356, DOI:10.1080/14786451.2012.748766.

Barry, Marie-Louise., Steyn, H. and Brent, A. (2011). "Selection of renewable energy technologies for Africa: Eight case studies in Rwanda, Tanzania and Malawi.", Renewable Energy: 36, 2845-2852.

Belonio, A., Larano, L., Ligisan, E., and Ocon, V. (2012). "An Indirect-Fired 6-Ton Capacity Grain Dryer with Biomass Furnace". April 2012. Retrieved 11th August, 2014 from: http://gasifiers.bioenergylists.org/files/if_6t_fb_grain_dryer-atb2012.pdf

Belward, A. Bisselink, B., Bódis, K., Brink, A., Dallemand, J.F., de Roo, A., Huld, T., Kayitakire, F., Mayaux, P., Moner-Girona, M., Ossenbrink, H., Pinedo, I., Sint, H., Thielen, J., Szabó, S., Tromboni, U., Willemen , L. (2011). "Renewable energies in Africa - Current Knowledge." Joint Research Committee (JRC) Scientific and Technical Reports. Retrieved on 12th March, 2014 from: https://ec.europa.eu/jrc/sites/default/files/reqno_jrc67752_final%2520report%2520.pdf

Bergert, D.L. (2000). "Management Strategies of Elaeis Guineensis (Oil Palm) in Response to Localized Markets in South Eastern Ghana, West Africa." Master of Science Thesis, Michigan Technological University.

Bernotat, K. and Sandberg, T. (2004). "Biomass fired small-scale CHP in Sweden and the Baltic States: a case study on the potential of clustered dwellings." Biomass and Bioenergy, 27(6), 521-530.

BioFerm. (2009). "Dry fermentation vs. Wet fermentation." Retrieved on 10th September, 2014 from: https://www.uwosh.edu/biodigester/internal-docs/fermenation

BoG- Bank of Ghana. (2014). [ONLINE] Available at: http://www.bog.gov.gh/index.php?option=com_wrapper&view=wrapper&Itemid=87, [Accessed 16 July 2014].

Bokanga, M. (1995). "Biotechnology and cassava processing in Africa." Food Technology: 49(1), 86-90.

Brew-Hammond, A. and Kemausuor, F. (2009). "Energy for all in Africa — to be or not to be?!." Curr Opin Environ Sustain 2009;1:83–8.

Bronicki, L. (2001). "ORMAT'S Experience in implementing Geothermal Projects. The Example of Olkaria III." ORMAT International, Inc.

Bryceson, S. and Shackleton, L. (2001). "Rural Africa at the crossroads: livelihood practices and policies." Natural resources perspective, overseas development, 52: 146 – 152.

Burrell, M.M. (2003). "Starch the need for improved quality or quantity and overview. " J. Exp. Bot. 218: 4574-4762.

CCRD/VACVINA. (2004). "Introduction to Construction Of Hybrid Bio-Digester – Vacvina." Retrieved 27th September, 2014 from: http://mon.danstagueule.fr.free.fr/NRJrealiste/biogaz/Biogaz_briques.pdf

Chambers, A. K., and Potter, I. (2002). "Gas utilization from sewage waste." Carbon and Energy Management, Alberta Research Council.

Chauvin, N.D., Mulangu, F. and Porto, G. (2012). "Food production and consumption trends in Sub-Saharan Africa: Prospects for the transformation of the agricultural sector." Working Paper No. 2012/011. United Nations Development Program. Regional Bureau for Africa, 76 pp.

Chen, Y. R. (1982). "Engineering properties of beef-cattle manure." ASAE paper no. 82-4085, ASAE, St Joseph, M1.

Chianu, J. N., Mairura, F., Ekise, I., and Chianu, J. N. (2008). "Farm input marketing in western Kenya: Challenges and opportunities." *African Journal of Agricultural Research*, *3*(3), 167-173.

Chong, C. N., and Zaharudin, I. (1988). "Biomass energy potential in Malaysia." ASEAN Journal of Science and Technology Development: 5(2), 15-27.

Chynoweth, D. P., Owens, J. M., and Legrand, R. (2001). "Renewable methane from anaerobic digestion of biomass." Renewable energy, 22(1), 1-8.

Cooke, R.D. and Maduagwu, E.N. (1978). "The effects of simple processing on the cyanide content of cassava chips." Journal Food Technology: 13, 299-306. In: Bulletin of Science, Technology & Society. Vol. 28, No. 2 (April). docrep/013/i1964e/i1964e00.htm.

Cordingley, J. E., Snyder, K. A., Rosendahl, J., Kizito, F. and Bossio, D. (2015). "Thinking outside the plot: addressing low adoption of sustainable land management in sub-Saharan Africa." Current Opinion in Environmental Sustainability, 15, 35-40.

Cuzin, N., Farinet, J.L., Segretain, C., and Labat, M. (1992). "Methanogenic fermentation of cassava peel using a pilot plug flow digester." Bioresource technology, 41(3), 259-264.

Dale, B.E. (2015). "A new industry has been launched: The Cellulosic Biofuels Ship (Finally) Sails." Biofuels, Bioprod & Bioref., Vol.9, pp 1-3.

Daniel, U., Pasch, Karl-Heinz, and Nayina, G.S. (2014). "Biogas in Ghana: Sub-Sector Analysis of Potential and Framework Conditions." Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry of Economic Affairs and Energy (BMWi). Retrieved on 12 February, 2015 from: http://www.giz.de/fachexpertise/downloads/giz2014-en-ghana-pdp-subsector-analysis-biogas.pdf

De Groote, H. (2013), "Economic analysis of maize storage technologies in East and Southern Africa". Agriculture and Food Security - Post-harvest Management (PHM) in Sub-Saharan Africa, Addis Ababa, October 29.

Dong, L., Liu, H., and Riffat, S. (2009). "Development of small-scale and micro-scale biomass-fuelled CHP systems–A literature review." Applied thermal engineering, 29(11), 2119-2126.

Duku, M.H., Gu, S. and Hagan, E.B. (2011). "A comprehensive review of biomass and biofuels potential in Ghana." Renewable & Sustainable Energy Reviews, 15(1): 404–41.

Dunmade, I. (2002). "Indicators of sustainability: Assessing the suitability of a foreign technology for a developing economy." Technology in Society: 24, 461-471.

Dziedzoave, N. T., Graffham, A.J., and Boateng, E.O. (2003). "Training manual on the production of high quality cassava flour." Training material produced under the DFID-funded research project on 'New Market for Cassava', Accra, Ghana.

Energica, (2009). "Pre-feasibility study for an improved cook stoves project in Northern Ghana." Report submitted to CARE Danmark, Danish Energy Agency, October. Retrieved on 13th August 2014 from: http://www.care.org/sites/default/files/documents/CC-2009-GHA-Cookstoves_Ghana.pdf

Er, A.C, Md. Nor, R. and Katiman, R. (2011). "Palm Oil Milling Wastes and Sustainable Development." American Journal of Applied Sciences: 8(5), 436-440.

Evald, A. (2005). "Renewable Energy Resources." Retrieved on 15th June, 2014 from: https://cdm.unfccc.int/filestorage/8/1/S/81S5NWVPRCHBEA7QGU2TDM4F9OZLKI/Enclosure%202.pdf?t=ZVV8bnQwbjVsfDAFE6OCYpcNulaz78IFWeYl

EVN- Electricity of Vietnam, (1999). "Rural Electrification Master Plan Study.", Vietnam.

Ezzati, M. and Kammen, D.M. (2002): "Household energy, indoor air pollution and health in developing countries: Knowledge Base for effective interventions." Annual review of energy and the environment (27).

Fadare, D.A., Bamiro O.A., and Oni, A.O. (2009). "Energy Analysis for Production of Powdered and Pelletised Organic Fertilizer in Nigeria." ARPN Journal of Engineering and Applied Sciences, vol. 4, no. 4, June.

Falade, K.O. and Akingbala, J.O. (2008). "Improved Nutrition and National Development through the Utilization of Cassava in Baked Foods." In: G.L. Robertson and J.R. Lupien (Eds), Using Food Science and Technology to Improve Nutrition and Promote National Development, International Union of Food Science & Technology.

FAO. (1977). "Processing of Cassava." Agricultural Services Bulletin No.8., ISSN 1020-0339.

FAO. (1992). "Maize in human nutrition." FAO Food and Nutrition Series, No. 25 , ISBN 92-5-103013-8, FAO, Rome (Italy).

FAO. (1997). "Constraints Analysis of the Post-Production Sector in Zambia." Retrieved 14th November, 2013, from: http://www.cd3wd.com/cd3wd_40/INPHO/VLIBRARY/MOVE_REP/X0288E/EN/X0288E10.HTM

FAO. (2002). "Small-scale palm oil processing in Africa." FAO Agricultural Services Bulletin 148, Rome, Italy.

FAO. (2011). "Southeast Asian forests and forestry to 2020: Subregional report of the second Asia-Pacific forestry sector outlook study." Bangkok. Retrieved 17th November, 2013 from: http://www.fao.org/ docrep/013/i1964e/i1964e00.htm

FAO. (2012). "Energy smart food at FAO: an Overview." Retrieved on 22nd September, 2014 http://www.fao.org/docrep/015/an913e/an913e.pdf

FAO/WHO. (1991). Joint FAO/WHO Food Standards Programme. Codex Alimentarius Commission XII, Supplement 4, FAO, Rome, Italy.

FAOSTAT. (2013). Retrieved 23rd September, 2013, from: http://faostat.fao.org/site/339/default.aspx

FAS- Foreign Agricultural Service. (2010). "Indonesia: Rising global demand fuels palm oil expansion." Commodity Intelligence Report. Washington, DC: U.S. Department of Agriculture. [Online] Available at http://www.pecad.fas.usda.gov/highlights/2010/10/Indonesia/ [Accessed 18 October,2013].

Ferry, R., and Monoian, E. (2012). "A Field Guide to Renewable Energy Technologies", Land art generator initiative: Retrieved on 16th September, 2013, from: www.landartgenerator.org

François, J., Abdelouahed, L., Mauviel, G., Feidt, M., Rogaume, C., Mirgaux, O., Patisson, F. and Dufour, A. (2012). "Estimation of the energy efficiency of a wood gasification CHP plant using Aspen Plus." Chemical Engineering Transactions, 29, 769-774.

Garfi, M., Gelman, P., Comas, J., Carrasco, W., and Fermer, I. (2011). "Agricultural reuse of the digestate from low- cost tubular digestates in rural Andean communities." Waste Manage. (Oxford) 31, 2584–2589.

GRA- Ghana Revevenue authority. (2014). [ONLINE]. Available at: http://www.gra.gov.gh/index.php/tax-information/income-tax [Accessed 25 October, 2014].

Greenland, D.J. and Nabhan, H. (2001). "Soil Fertility Management in Support of Food Security in Sub-Saharan Africa." Food and Agriculture Organization of the United Nations, Rome, 13: 9251045631.

GSS- Ghana Statistical Service. (2008). **"**Ghana Living Standards Survey Report of the Fifth Round (Glss 5)**",** September.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. and Meybeck, A. (2011). "Global Food Losses and Food Waste: Extent, Causes and Prevention." Food and Agriculture Organization of the United Nations, Rome, Italy.

GWEC- Global Wind Energy Council. (2011). "Global Wind Report; Annual Market Update 2010." Retrieved on 15th December, 2013, From: http://www.gwec.net/fileadmin/images/Publications/GWEC_annual_market_update_2010_- 2nd_edition_April_2011.pdf

Hall, D.O., Rosillo-Calle, F., and De Groot, P. (1992). "Biomass Energy-Lessons from Case Studies in Developing Countries." Energy Policy: January, 62-73.

Haung, L., Lu, W., and Li, X. (2009). "Study on emerging technology selection and evaluation by technology foresight and fuzzy consistent matrix." In: PICMET 2009 Proceedings, pp. 441.

Heldman, D.R. and Hartel, R.W. (1997). "Principles of Food Processing." New York: Chapman and Hall.

Hicks, P. A., 1995. "An Overview of Issues and Strategies in the Development of Food Processing Industries in Asia and the Pacific." In: Growth of the Food Processing Industry in Asia and the Pacific, APO, Tokyo, Japan.

Holm – Nielsen, J.B., Seadi, J. A., and Oleskowicz – Popiel, P. (2009). "The future of anaerobic digestion and biogas utilization." Bioresource Technology 100 (2009). Pp. 5478 – 5484.

Hon, J. L. M. (2010). "A case study on palm empty fruit bunch as energy feedstock." SEGi Rev, 3, 3-15.

Hornal, D., Timpo, S. and Gruère, G. (2007). "Marketing underutilized crops: The case of the African garden egg (Solanum aethiopicum) in Ghana." Global Facilitation Unit for Underutilized Species (GFU) Via dei Tre Denri, Rome, Italy.

Hounhouigan, D.J., Sekpe, H.G., Kayodé, A.P., Mestres, C. and Nago, C.M. (2003). "Mechanization of maize degerming for mawe production." In Maize revolution in West and Central Africa. Ed B. Badu-Apraku. Wecaman, IITA Ibadan Nigeria, pp 453-462.

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D. and Dudgeon, D. (2011). "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover." National Renewable Energy Laboratory, Technical Report, NREL/TP-5100-47764, May.

Husain Z., Zainal, Z.A. and Abdullah, M.Z. (2003). "Analysis of Biomass-Residue-Based Cogeneration System in Palm Oil Mills." Biomass and Bioenergy: 24, 117–124.

IAASTD. (2009). "Agriculture at a crossroads: Sub-Saharan Africa (SSA) report (Vol. V)." International Assessment of Agricultural Knowledge, Science and Technology for Development. Washington, DC: Island Press.

IEA- International Energy Agency. (2004). "Energy Statistics and Balances of Non-OECD Countries." Paris: OECD/IEA.

IEA- International Energy Agency. (2008). "From 1st- to 2nd-Generation Biofuel Technologies: An Overview of Current Industry and RD&D Activities." OECD/IEA, Paris.

IEA- International Energy Agency. (2011a). "Renewable Energy Markets and Prospects by Region." IEA information paper, OECD/IEA, Paris.

IEA- International Energy Agency. (2011b). "Energy statistics." Retrieved 14th December, 2013, from: http://www.iea.org/stats//www.mpoc.org.my

IEA- International Energy Agency. (2014). "Africa Energy Outlook: A focus on energy prospects in sub-Saharan Africa." World energy outlook special report. Retrieved 18th September, 2014 from:

https://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf

IFAD. (2011). "Facts & Figures: Rural poverty report 2011." Retrieved on 10th June 2015 from: http://www.ifad.org/rpr2011/media/kit/factsheet_e.pdf

IITA- International Institute of Tropical Agriculture. (1990). "Cassava in tropical Africa: A reference manual." International Institute of Tropical Agriculture, Ibadan, Nigeria.

IITA- International Institute of Tropical Agriculture. (2014). [ONLINE] Available at: http://www.iita.org/maize [Accessed 15 March 2014].

IRENA- International Renewable Energy Agency. (2011). "Prospects for the African Power Sector: Scenarios and Strategies for Africa Project." Retrieved on 20th August, 2013 from:https://www.irena.org/DocumentDownloads/Publications/Prospects_for_the_African_PowerSector.pdf

IRENA- International Renewable Energy Agency. (2012a). "Renewable Energy Technologies: Cost Analysis Series." Biomass for Power Generation, Volume 1: Power Sector, Issue 5/5, June.

IRENA- International Renewable Energy Agency. (2012b). "Summary for Policy Makers: Renewable Power Generation Costs." Retrieved on 12th September, 2013 from: https://www.irena.org/DocumentDownloads/Publications/Renewable_Power_Generation_Costs.pdf

Iwuoha, C.I., and Eke, S.O. (1996). "Nigerian indigenous fermented foods: their traditional process operation, inherent problems, improvements and current status." Food Research International: 29(5-6), 527-540.

Jekayinfa, S.O. and Bamgboye, A.I. (2006). "Estimating energy requirement in cashew (Anacardium occidentale L.) nut processing operations". Energy 31: 1305–1320.

Jekayinfa, S.O. and Bamgboye, A.I. (2008). "Energy use analysis of selected palm-kernel oil mills in south western Nigeria." Energy: 33, 81–90.

Jekayinfa, S.O. and Olajide, J.O. (2007). "Analysis of Energy Usage in the Production of three Selected Cassava-based Foods in Nigeria". Journal of Food Engineering 82: 217–226.

Jekayinfa, S.O. and Scholz, V. (2013). "Laboratory Scale Preparation of Biogas from Cassava Tubers, Cassava Peels, and Palm Kernel Oil Residues." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 35:21, 2022-2032, DOI: 10.1080/15567036.2010.532190

Jensen, J. (2010). "Local and Regional Food Systems for Rural Futures." RUPRI Rural Futures Lab, Foundation Paper No. 1, November.

Jha, A.K. (2012) "Biowaste: Dry Advice." [ONLINE] Available at: http://waste-management-world.com/a/biowaste-dry-advice [Accessed 28 November 2015].

Junior, O., Costa, N.M.B., Martino, H.S.D., and Paes, M.C.D. (2014). "Chemical composition and effects of micronized corn bran on iron bioavailability in rats." Food Science and Technology (Campinas), 34(3), 616-622.

Kantai, P. (2002). "Hot and Dirty: Inside Kenya's 23 billion shilling charcoal industry." Nairobi: Environment Liaison Centre International. EcoForum: 24(4).

Karekezi, S. (2002). "Renewables in Africa – Meeting the Energy Needs of the Poor, Special Issue – Africa: Improving Modern Energy Services for the Poor." Energy Policy: 30, 11-12

Karekezi, S. and Kimani, J. (2002). "Status of Power Sector Reform on the Poor." Energy Policy, Vol. 3, Nos. 11-12, Special Issue – Africa: Improving Modern Energy Services for the Poor: Elsevier Science Limited.

Karekezi, S. and Kithyoma W. (2003). "Renewable energy in Africa: prospects and limits." In: Proceedings of the workshop for African energy experts; 2–4, June 2003.

Karekezi, S. Majoro, L., and Kithyoma, W. (2002). "Renewable Energy Technologies in Africa – An Energy Training Course Handbook." AFREPREN Occasional Paper No. 10: AFREPREN, Nairobi, Kenya.

Karekezi, S., and Kimani, J. (2002). "Status of Power Sector Reform on the Poor, Special Issue – Africa: Improving Modern Energy Services for the Poor." Energy Policy: 30, 11-12.

Karekezi, S., and Ranja, T. (1997). "Renewable Energy Technologies in Africa". ZED Books and AFREPREN. Oxford U.K.

Karki B.A, Gautam, K.M. and Karki, A. (1994). "Biogas Installation from Elephant Dung at Machan Wildlife Resort, Chitwan, Nepal." Biogas Newsletter, Issue No. 45.

Karki, B.A. and Dixit, K. (1984). "Biogas Fieldbook." Sahayogi Press, Kathmandu, Nepal.

Kempegowda, R. S., Skreiberg, Ø. and Tran, K. Q. (2012). "Techno-economic evaluations of various biomass CHP technologies and policy measures under Norwegian conditions." Energy Procedia, 20, 1-10.

Kerdsuwan, S. and Laohalidanond, K. (2011). "Renewable Energy from Palm Oil Empty Fruit Bunch." Renewable Energy - Trends and Applications, Dr. Majid Nayeripour (Ed.), ISBN: 978-953-307-939-4, InTech, Retrieved on 18th February, 2014 from: http://cdn.intechopen.com/pdfs-wm/22681.pdf

Kleih, U., Philips, D., Wordey, T.M. and Komlaga, G. (2013). "Cassava Market and Value Chain Analysis, Ghana Case Study." Final Report, January.

Kolade, O. O., Coker, A. O., Sridhar, M. K. C. and Adeoye, G. O. (2006). "Palm kernel waste management through composting and crop production." Journal of Environmental Health Research, 5(2), 81-85.

Kreamer, R. G. (1986). "Gari Processing In Ghana: A Study of Entrepreneurship and Technical Change in Tropical Africa." December 1986, A.E. Research: 86-30.

Kuboye, A. O. (1985). "Traditional fermented foods and beverages of Nigeria." In Proc. Intl Foundation for Science (IFS)/United Nations University (UNU) Workshop on"Development of Indigenous Fermented Foods and Food Technology in Africa". Douala, Cameroon, 14-18 October, pp. 225-236.

Kurkela, E. (2010). "Thermal Gasification for Power and Fuels." VTT, Finland.

Kyei-Baffour, N. and Manu, C. (2008). "Small-scale palm oil process improvement for poverty alleviation and national development." Proceedings of 3rd International Conference on Appropriate Technology, November 12-15, 2008 at Serena Hotel, Kigali, Rwanda.

Lado, C. (1992). "Labour Participation In Agricultural Production And The Implications For Nutrition And Health In Rural Africa." Soc. Sci. Med.: 34 (7), 789-807.

Lambe, F., Jürisoo, M., Wanjiru, H., and Senyagwa, J. (2015). "Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action." Prepared by the Stockholm Environment Institute, Stockholm and Nairobi, for the New Climate Economy. Available at: http://newclimateeconomy.report/misc/working-papers.

Larson, E. D. and Kartha S. (2000). "Bio Energy Primer: Modernised Biomass Energy for Sustainable Development." United Nations Development Programme (UNDP).

Lartey, B. L. (1975). "Some technological transformation and research needs in Ghana's indigenous food industries." UNIDO Joint Consultation on Promotion of Industrial Research and Services in Africa, Lagos, 15-22 September.

Lau, P.C., Machado, Gilmara de Oliveira., Nogueira, L.A.N., Christoforo, A.L., Gonçalves, D. and Lahr, F.A.R., (2013). "Evaluation of the Energy Efficiency of Wood Stove from Irati Brazilian City." International Journal of Agriculture and Forestry, 3(7): 267-272

Lauer, M. (2008) "Methodology guideline on techno economic assessment (TEA)." Workshop WP3B Economics, Methodology Guideline.

Leibbrandt, N.H. (2010). "Techno-economic study for sugarcane bagasse to liquid biofuels in South Africa: A comparison between biological and thermochemical process routes." Doctoral dissertation, Department of Process Engineering, University of Stellenbosch, South Africa.

Lim, K. O. (1998). "Oil Palm Plantations – A Plausible Renewable Source of Energy." Reric International Energy Journal: 20(2), 112-114.

Lim, K.H. (1988). "Integrated systems for treating and utilizing plantation effluents: palm oil mill effluent as a specific example." In Anaerobic Digestion 1988, Hall, E.R.; and Hobson, P.N. (Eds.). Oxford: Pergamon Press, pp 303-313.

Lim, L. Q. (2010). "Comparative Study of an Open Lagoon with High Efficient Methane Free Treatment Plant and Cdm Project in Palm Oil Mill Effluent." Universiti Malaysia Pahang. Retrieved 19th September, 2013, from:

Maarita, N. O. (2002). "The Impact of Large Scale Energy Development on the Poor: Environmental and Social Economic Impact of a Geothermal Power Plant on a poor Rural Community in Kenya." Energy Policy, 2002.

Mahlia T.M.I., Abdulmuin M.Z., Alamsyah T.M.I. and Mukhlishien, D. (2001). "An Alternative Energy Source from Palm Waste Industry for Malaysia and Indonesia." Energy Conversion and Management: 42, 2109 – 2118.

Martinez, S., Hand, M., Da Pra, M., Pollack, S., Ralston, K., Smith, T., Vogel, S., Clark, S., Lohr, L., Low, S. and Newman, C. (2010). "Local food systems: Concepts, impacts and issues." Economic Research Report No. 97. Washington, DC: ERS/USDA.

Mata-Alvarez, J. (2002). "Biomethanization of the Organic Fraction of Municipal Solid Wastes." IWA Publishing.

May, J. B. (1987). "Wet Milling: Process and Products." In: S. A. Watson, and Ramstad, Paul E. (Ed.), Corn: Chemistry and Technology (pp. 377-397). St. Paul, MN: American Association of Cereal Chemists.

Mbohwa, C. (2003). "Bagasse energy cogeneration potential in the Zimbabwean sugar industry." Renewable energy, 28: 191-204.

McKendry, P. (2002). "Energy production from biomass (part 2): conversion technologies." Bioresource technology, 83(1), 47-54.

MiDA (2009). "Investment opportunity in Ghana; Maize, Soya and Rice production and processing." Millennium Development Authority (MiDA), Accra-Ghana, 2009.

Mills, D. (2004), "Advances in solar thermal electricity technology." solar Energy, 76(1), 19-31.

MoFA- Ministry of Food and Agriculture, Republic of Ghana. (2012). [Online] Available at http://mofa.gov.gh/site/?page_id=11395 [Accessed on 12 September, 2014].

MoFA- Ministry of Food and Agriculture, Republic of Ghana. (2013) –Ministry of Food and Agriculture; Veterinary Services Directorate, December 2013.

Möller, K. and Stinner, W. (2009). "Effects of different manuring systems with and without biogas digestion on soil mineral nitrogen content and on gaseous nitrogen losses (ammonia, nitrous oxides)." In: European Journal of Agronomy, 30 (2009), pp. 1–16.

Monceaux, D. A. (2009). "Alternative feedstocks for fuel ethanol production." In: The Alcohol Textbook: A Reference for the beverage, fuel and industrial alcohol industries, Ingledew, W. M., Kelsall, D. R., Austin, G. D. & Kluhspies, C. Nottingham University Press, Nottingham. ISBN 978-1-904761-65-5. pp. 47-71.

Monteiro, C.A. and Levy, R.B. (2010). "A new classification of foods based on the extent and purpose of their processing." Public Health Nutrition, 26(11):2039-2049.

Muradin, M. and Foltynowicz, Z. (2014). "Potential for producing biogas from agricultural waste in rural plants in poland." Sustainability, 6(8), 5065-5074.

Nang'ayo, F., Omanya, G., Bokanga, M., Odera, M., Muchiri, N., Ali, Z., and Werehire, P. (2005). "A strategy for industrialisation of cassava in Africa." Proceedings of a small group meeting, 14–18 November 2005, Ibadan, Nigeria and Nairobi, Kenya: African Agricultural Technology Foundation.

Ndegwa, G., Breuer, T., and Hamhaber, J. (2011). "Woodfuels in Kenya and Rwanda: powering and driving the economy of the rural areas." *Rural*, *45*(2), 26-30.

Nguyen, K. Q. (2007). "Alternatives to grid extension for rural electrification: Decentralized renewable energy technologies in Vietnam." Energy Policy: 35, 2579–2589.

Nordin, N. I. A. A., Ariffin, H., Andou, Y., Hassan, M. A., Shirai, Y., Nishida, H., and Ibrahim, N. A. (2013). "Modification of oil palm mesocarp fiber characteristics using superheated steam treatment." Molecules, 18(8), 9132-9146.

Nsaful, F. (2012). "Process Modelling of Sugar Mill Biomass to Energy Conversion Processes and Energy Integration of Pyrolysis." Master's thesis, Department of Process Engineering, University of Stellenbosch, South Africa.

Nweke, F. (2009). "Controlling Cassava Mosaic Virus and Mealybug in Sub-Saharan Africa." International Food Policy Research Institute (IFPRI), Discussion Paper 00912, November.

Nweke, F. I., Spencer, D. S. C. and Lynam, J. K. (2002). "The cassava transformation: Africa's best kept secret." East Lansing: Michigan State University Press.

Nyirenda, D.B., Chiwona-Karltun, L., Chitundu, M., Haggblade S., and L. Brimer. (2011). "Chemical safety of cassava products in regions adopting cassava production and processing – Experience from Southern Africa." Food and Chemical Toxicology: 49, 607–612.

Ofosu-Budu, K. and Sarpong, D. (2013) "Oil palm industry growth in Africa: A value chain and smallholders study for Ghana." In: Elbehri, A. (Ed.) Rebuilding West Africa's Food Potential. FAO/IFAD.

Ohimain, E.I., Daokoru-Olukole, C., Izah, S.C. and Alaka, E.E. (2012). "Assessment of the quality of crude palm oil produced by smallholder processors in Rivers State, Nigeria." Niger J. Agric. Food Environ, 8(2): 28 – 34.

Ohimain, E.I., Izah, S.C. and Abah, S.O. (2013). "Air quality impacts of smallholder oil palm processing in Nigeria." J. Environ. Protection: 4, 83-98.

Olisa, Y.P. (2014). "Utilization of Palm Empty Fruit Bunch (pefb) As Solid Fuel for Steam Boiler." European Journal of Engineering and Technology, Vol. 2 No. 2, 2014, ISSN 2056-5860.

Olukunle, O.J (2005). "Development of a Cassava Peeling Machine." Conference on International Agricultural Research for Development, Stuttgart-Hohenheim, October 11-13, 2005.

Otim, G., Okaka, D., and Kayima, J. (2011). "Design of Biogas Plant for Rural Households in Uganda (Case Study: Apac District)." The Second International Conference on Advances in Engineering and Technology, AET2011, 31st January - 2nd February, Makarere University Kampala/Uganda. Retrieved on 18th March, 2015 from: http://news.mak.ac.ug/documents/Makfiles/aet2011/Otim%20(2).pdf

Ouaouich, A. (2004). "Small-scale Cereal Milling and Bakery Products: Production Methods, Equipment and Quality Assurance Practices." UNIDO Technology Manual, pp 1-111.

Owamah, H.I., Dahunsi, S.O., Oranusi, U.S., and Alfa, M.I. (2014). "Fertilizer and sanitary quality of digestate biofertilizer from the co-digestion of food waste and human excreta." Waste Management, 34 (2014), 747–752.

Panapanaan, V., Helin, T., Kujanpää, M., Soukka, R., Heinimö, J. and Linnanen, L. (2009). "Sustainability of palm oil production and opportunities for Finnish technology and know-how transfer." Research Report/Lappeenranta University of Technology, Faculty of Technology, LUT Energy.

Panichnumsin, P., Nopharatana, A., Ahring, B., and Chaiprasert, P. (2010). "Production of methane by co-digestion of cassava pulp with various concentrations of pig manure." Biomass and Bioenergy, 34(8), 1117-1124.

Pauli, G. (1998). "Upsizing: The road to zero emissions. More jobs, More Income and No Pollution." London: Green Leaf Publishing.

Pedersen, M. and Meyer. S.A. (2010) "Lignocellulose pretreatment severity – relating pH to biomatrix opening." New Biotechnology, 27(6), pp 739-750.

Peters, M. and Timmerhaus, K. (2003). "Plant Design and Economics for Chemical Engineers." 5th Edition. New York: McGraw-Hill.

Puig-Arnavat, M., Carles Bruno, J., and Coronas, A. (2010). "Review and analysis of biomass gasification models." Renewable and Sustainable Energy Reviews 14, 2841–2851.

PURC- Public Utility Regulations Commission. (2013). "Publication of Feed-In Tariffs for electricity generated from renewable energy sources", Accra.

PURC- Public Utility Regulations Commission. (2014). "Press Release on 2014 First Quarter Automatic Adjustment Formula." Retrieved on 25th June, 2014 from: http://www.purc.com.gh/purc/sites/default/files/press_release_on_aaf.pdf

Quah, S.K. and Gilles, D. (1981). "Practical Experience in Production and Use of Biogas. Proceedings of National Workshop on Oil Palm By-Product Utilisation." PORIM, pp. 119 – 125.

Quaye, W., Gayin, J., Yawson, I. and Plahar, W.A. (2009). "Characteristics of Various Cassava Processing Methods and the Adoption Requirements in Ghana." Journal of Root Crops: 35, 59-68.

Rabirou, K., Ayanwale, A. B., Idowu, E. O. and Williams, S. B. (2012). "Effect of rural transportation system on agricultural productivity in Oyo State, Nigeria." Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS), 113(1), 13-19.

Ram, B., (2006). "Renewable Energy Development in Africa - Challenges, Opportunities, Way Forward." South Africa Regional Office, African Development Bank. Retrieved on 12th September, 2013 from:
http://www.indiaenergycongress.in/montreal/library/pdf/275.pdf

Reddy, A., Williams, R. H. and Johansson, T.B. (1997). "Energy After Rio: Prospects and Challenges" UNDP, New York.

Reij, C. P., and Smaling, E. M. A. (2008). "Analyzing successes in agriculture and land management in Sub-Saharan Africa: Is macro-level gloom obscuring positive micro-level change?." Land Use Policy, 25(3), 410-420.

REN21 (2010). "Renewables 2010: Global Status Report." Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 80 pp.

Renewable Energy Association (2009). "Energy and environment." [Online] Available at http: //www.r-ea. net/info/energy-info [Accessed 20th October, 2013].

Ruth, M., Mai, T., Newes, E., Aden, A., Warner, E., Uriarte, C., Inman, D., Simpkins, T., and Argo, A. (2013). "Projected Biomass Utilization for Fuels and Power in a Mature Market." Transportation Energy Futures Series. Prepared for the U.S. Department of

Energy by National Renewable Energy Laboratory, Golden, CO. DOE/GO-102013-3707. 153 pp.

Saifuddin, N. and Fazlili, S.A. (2009). "Effect of microwave and ultrasonic pretreatments on biogas production from anaerobic digestion of palm oil mill effluent." American Journal of Engineering and Applied Sciences 2, 139–146.

Samer, M. (2012). "Biogas plant constructions." In: Kumar S (ed) Biogas. InTech, Rijeka, pp 343–368. doi:10.5772/31887. ISBN 978-953-51-0204-5.

Sanni, A. I. (1993) "The need for process optimization of African fermented foods and beverages." Int. J. Food Microbiol., 18, 85-95.

Sathaye, J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, S. Kadner, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin (2011): Renewable Energy in the Context of Sustainable Development. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sefa-Dedeh, S. (1993). "Traditional food technology." In: R. Macrae, R. Robinson, & M. Sadler (Eds.), Encyclopedia of food science, food technology and nutrition (pp. 4600–4606). New York: Academic Press.

Sen, R. and Annachhatre, A. P. (2015). "Effect of air flow rate and residence time on biodrying of cassava peel waste." International Journal of Environmental Technology and Management, 18(1), 9-29.

Serpagli, A., Nagori, G.P., Amoriggi, G., and Calvosa, C. (2010a). "Squaring the circle: how food and fuel can be produced in a complementary and not competitive manner - the use of cassava wastes to produce energy." Outcomes of a feasibility study implemented in Nigeria, IFAD, Africa I Division, March.

Serpagli, A., Nagori, G.P., Amoriggi, G., and Calvosa, C. (2010b). "The use of cassava wastes to produce energy: outcomes of a feasibility study implemented in Ghana." In collaboration with the IFAD-funded "Root & Tuber Improvement and Marketing Programme/RTIMP" of Ghana, October.

Shimizu, H. and Desrochers, P. (2012). "The health, environmental and economic benefits of palm oil." IEM's Economic Note, September. Retrieved on 19th July, 2014 from: http://www.institutmolinari.org/IMG/pdf/note0912_en.pdf

Singh, P. (1986) "Energy in Food Processing." Elsevier Science Publishing Company Inc. New York.

SNV. (2011). "Technology and Mass- Dissemination Experiences from Asia." Biogas compact course PPRE- Oldenburg University, April 26 - 28.

Sommart, K. and Pipatmanomai, S. (2011). "Assessment and Improvement of Energy Utilization in Crude Palm Oil Mill." 2011 International Conference on Chemistry and Chemical Process IPCBEE vol.10 (2011), IACSIT Press, Singapore.

Sorensen, B. (1991). "A history of renewable energy technology." Renewable series, Butterworth-Heinmann.

Stecher, K., Brosowski, A., and Thrän, D. (2013). "Biomass potential in Africa." Report prepared by Deutsches Biomasseforschungszentrum gGmbH (DBFZ) for International Renewable Energy Agency (IRENA). Retrieved on 20th September, 2014 from: https://www.irena.org/DocumentDownloads/Publications/IRENA-DBFZ_Biomass%20Potential%20in%20Africa.pdf

Steger, U. (2005). "Sustainable development and innovation in the energy sector." Berlin: Springer.

Sulaiman, A., Zakaria, M.R., Hassan, M.A., Shirai, Y. and Busu, Z. (2009). "Co-Digestion of Palm Oil Mill Effluent and Refined Glycerin Wash Water for Chemical Oxygen Demand Removal and Methane Production." Am. J. Environ. Sci.: 5, 639-646.

Taiwo, K. A., Oladepo, W. O., Ilori, M. O. and Akanbi, C. T. (2002). "A study on the Nigerian food industry and the impact of technological changes on the small-scale food enterprises." Food Reviews International, 18(4):243–262.

Taiwo, K.A., Owolarafe, O.K., Sanni, L.A., Jeje, J. O., Adeloye, K., and Ajibola, O.O. (2000). "Technological Assessment of palm oil production in Osun and Ondo States of Nigeria." Technovation: 20, 215-223.

Taylor, R. (2006). "Solar thermal technology and applications." NREL, June 27-29, pp. 7

The World Bank. (2012). "Agribusiness Indicators: Ghana." Economic and Sector Work, Report Number 68163-GH.

Thorne, P.J., Thornton, P.K., Kruska, R.L., Reynolds, L., Waddington, S.R., Rutherford A.S., and Odero, A.N. (2002). "Maize as food, feed and fertiliser in intensifying crop-livestock systems in East and southern Africa: An exante impact assessment of technology interventions to improve smallholder welfare." ILRI Impact Assessment Series 11. ILRI (International Livestock Research Institute), Nairobi, Kenya. 123 pp.

Toenniessen, G., Adesina, A. and DeVries, J. (2008). "Building an alliance for a green revolution in Africa." Annals of the New York academy of sciences, 1136(1), 233-242.

Tong, S.L. and Jafaar, A. (2005). "POME Biogas Capture, Upgrading & Utilisation". Proceedings of the PIPOC 2005 International Palm Oil Congress (Chemistry and Technology).

Torero, M. and Chowdhury, S. (2005). "Increasing access to infrastructure for Africa's rural poor." International Food Policy Research Institute (IFPRI), Washington, DC.

Truswell, A.S. and Brand, J.C. (1985). "Processing food." British Medical Journal, 291(6503):1186-90.

Tumwseige, V., Avery, L.M., Austin, G., Balana, B.B., Bechtel, K., Casson, E., et al. (2012). "Small-scale biogas digester for sustainable Energy production in Sub-Saharan Africa." In: Proceedings of 1st World Sustainability Forum, [electronic conference]. Basel, Switzerland: MDPI; 2012.

Udoetok, I.A. (2012). "Characterization of ash made from oil palm empty fruit bunches (oefb)." International Journal of Environmental Sciences, Volume 3, No. 1.

Ugwu, K., and Agbo, K. (2013). "Evaluation of Binders in the Production of Briquettes from Empty Fruit Bunches of Elais Guinensis." International Journal of Renewable and Sustainable Energy, 2(4), pp. 176-179. doi:10.11648/j.ijrse.20130204.17.

Ukwuru, M.U. and Egbonu, S.E. (2013). "Recent development in cassava-based products research." Acad. J. Food. Res. 1(1): 001-013.

UNCTAD- United Nations Conference on Trade and Development, (2010). "UNCTAD Current Studies on Science, Technology and Innovation: Renewable Energy Technologies for Rural Development." United Nations Conference on Trade and Development (UNCTAD), UNCTAD/DTL/STICT/2009/4, New York and Geneva.

UNIDO- United Nations Industrial Development Organization. (2009). "Scaling up Renewable Energy in Africa." 12th Ordinary Session of Heads of State and Governments of the AFRICAN UNION, January. Addis Ababa, Ethiopia.

US EPA. (2007). "Catalog of CHP Technologies." Report prepared for U. S. Environmental Protection Agency Combined Heat and Power Partnership, v.1.1, September 2007. Retrieved on 2nd March, 2013 from: http://www.epa.gov/chp/documents/biomass_chp_catalog.pdf

US EPA. (2008). "Catalog of CHP Technologies." December.

USDA- United States Department of Agriculture (2009) "Indonesia: Palm oil production growth to continue." [ONLINE] Available at: http://www.pecad.fas.usda.gov/highlights/2009/03/Indonesia/ [Accessed 5 April, 2014].

Uzogara, S. G., Agu, L. N. and Uzogara, E. O. (1990). "A review of traditional fermented condiments and beverages in Nigeria: Their benefits and possible problems." Ecol. Food Nutr.: 24, 267-288.

VRA- Volta River Authority. (2014). "Power Outlook – Facts and Figures." [ONLINE] Available at: Available online: http://www.vra.com [Accessed 20 July, 2014].

Wang, L. (2009). "Energy Efficiency and Management in Food Processing Facilities." Taylor & Francis Group (CRC press), ISBN-13: 978-1-4200-6338-7, Boca Raton.

Wiredu, N.A., Gyasi, K.O., Abdoulaye, T., Sanogo, D. and Langyintuo, A. (2010). "Characterization of maize producing households in the northern region of Ghana." Country Report Ghana CSIR/SARI-IITA, Ibadan, Nigeria.

Wirsiy, E.B. (2013). "Assessment of the effectiveness of biogas slurry as biofertilizer for vegetable gardening in Kumbo, Cameroon: case of Solanum scabrum." Masters dissertation, Department of Plant Biology, University of Yaounde, Cameroon.

World Bank. (2000). "ESMAP Household Energy Strategy." Leaflet.

World Bank. (2006). "African Development Indicators." Washington DC: World Bank.

World Bank. (2008). "World Development Report 2008: Agriculture for Development." World Bank, Washington, D.C.

www.alibaba.com. [Accessed 15 June 2014].

www.mywage.org/ghana/home/salary/salary-check [Accessed 21 September, 2014].

Yacob, S., Hassan, M.A., Shirai, Y., Wakisaka, M. and Subash, S. (2005). "Baseline study of methane emission from open digesting tanks of palm oil mill effluent treatment." Chemosphere: 59, 1575–1581.

Yeoh, B. G. (2004). "A Technical and Economic Analysis of Heat and Power Generation from Biomethanation of Palm Oil Mill Effluent." International Energy Journal: 6, 20-63.

Youngs, H. and Sommerville, C. (2014). "Best Practices for Biofuels: Data-based standards should guide biofuel production." Science, 6th June 2014. Vol. 344, Issue 6188, pp 1095-1096.

Yusoff, S. (2006). "Renewable Energy from Palm Oil - Innovation on Effective Utilization of Waste." Journal of Cleaner Production: 14, 87-93.

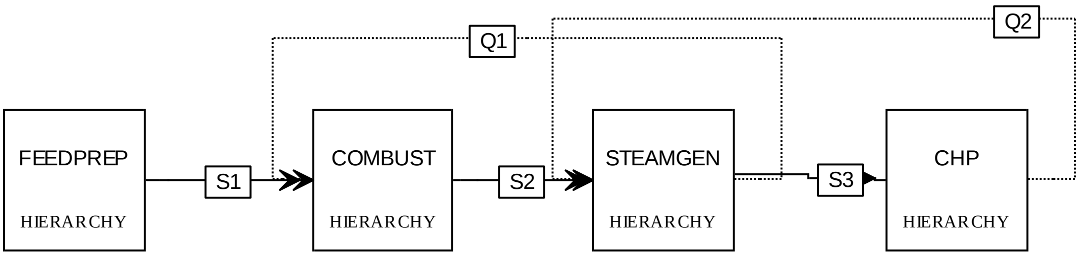
Zhu, H., Sun, L., Zhang, Y., Zhang, X. and Qiao, J., (2012). "Conversion of spent mushroom substrate to biofertilizer using a stress-tolerant phosphate-solubilizing Pichia farinose FL7." Bioresour. Technol. 111, 410–416.

Zu, K.S.A., Adjei-Nsiah, S., and Bani, R.J. (2012). "Effect of processing equipment and duration of storage of palm fruits on palm oil yield and quality in the Kwaebibrem District, Ghana." Agricultural Research and Reviews: 1(1), 18 – 25.

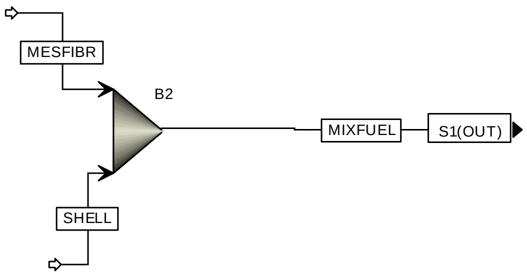
APPENDIX A: PROCESS FLOW DIAGARAMS OF THE RESIDUES-TO-IN-HOUSE ENERGIES MODELS

NB: To avoid repetition of similar process modelling approaches in the Aspen plus® simulation software, the cassava peels/cattle dung biogas to power process was not presented due to its similarity to the POME biogas gas-gen process. Furthermore, in all the presented energy processes, only relevant stream data for completing the material balances were given.

A1: Process flow diagram and stream data for CPO mill solid residue to in-house CHP (13 tons FFB/hr) theoretical scenario 1 (efb excluded)

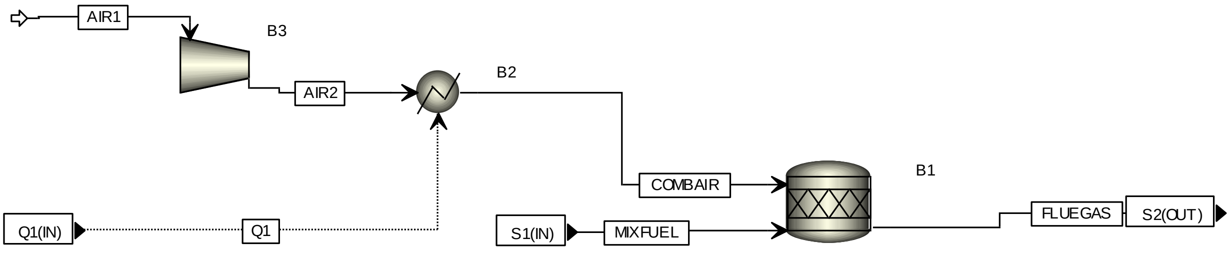


FEEDPREP HIERARCHY



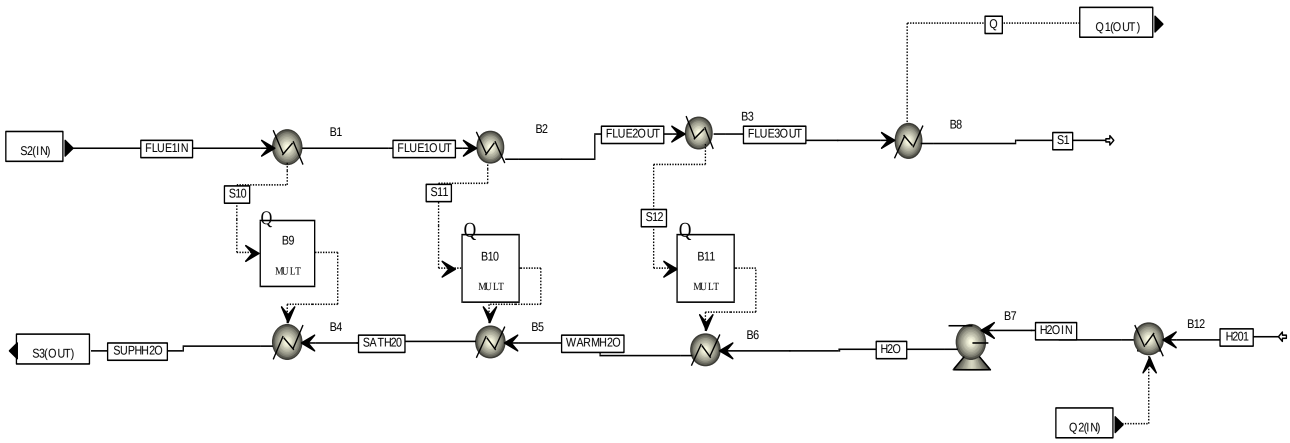
	MESFIBR	MIXFUEL	SHELL
Temperature C	25	25	25
Pressure bar	1	1	1
Vapor Frac	0	0	0
Mass Flow kg/hr			
LIGNIN	392	558	166
HEMICEL	526	728	202
CELLULOS	836	1381	545

COMBUST HIERARCHY



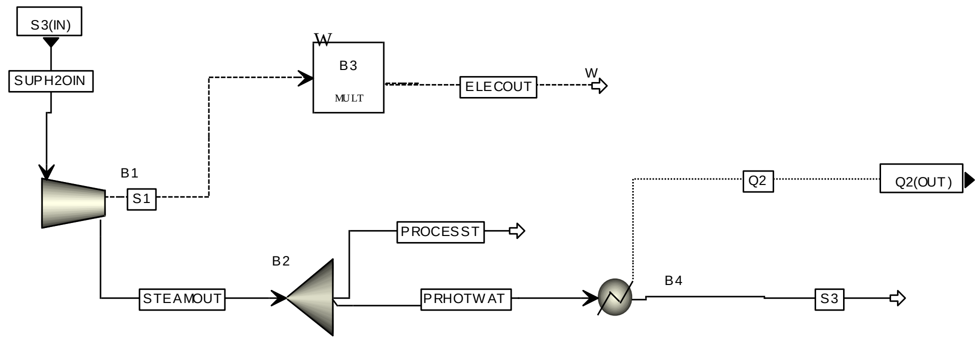
	AIR1	AIR2	COMBAIR	FLUEGAS	MIXFUEL
Temperature C	25	37	250	1601	25
Pressure bar	1	1.5	1.5	1	1
Vapor Frac	1	1	1	1	0
Mass Flow kg/hr					
N2	16746	16746	16746	16746	0
O2	5054	5054	5054	1538	0
H2O	0	0	0	1429	0
CO2	0	0	0	4755	0
LIGNIN	0	0	0	0	558
HEMICEL	0	0	0	0	728
CELLULOS	0	0	0	0	1381

STEAMGEN HIERARCHY



	FLUE1IN	FLUE1OUT	FLUE2OUT	FLUE3OUT	H2O	H2OIN	S1	SATH20	SUPHH2O	WARMH2O
Temperature C	1601	1000	600	350	41	41	120	243	400	160
Pressure bar	1	1	1	1	25	1	1	35	32	35
Vapor Frac	1	1	1	1	0	0	1	0	1	0
Mass Flow kg/hr										
N2	16746	16746	16746	16746	0	0	16746	0	0	0
O2	1538	1538	1538	1538	0	0	1538	0	0	0
H2O	1429	1429	1429	1429	10675	10675	1429	10675	10675	10675
NO2	0	0	0	0	0	0	0	0	0	0
SO2	0	0	0	0	0	0	0	0	0	0
CO2	4755	4755	4755	4755	0	0	4755	0	0	0

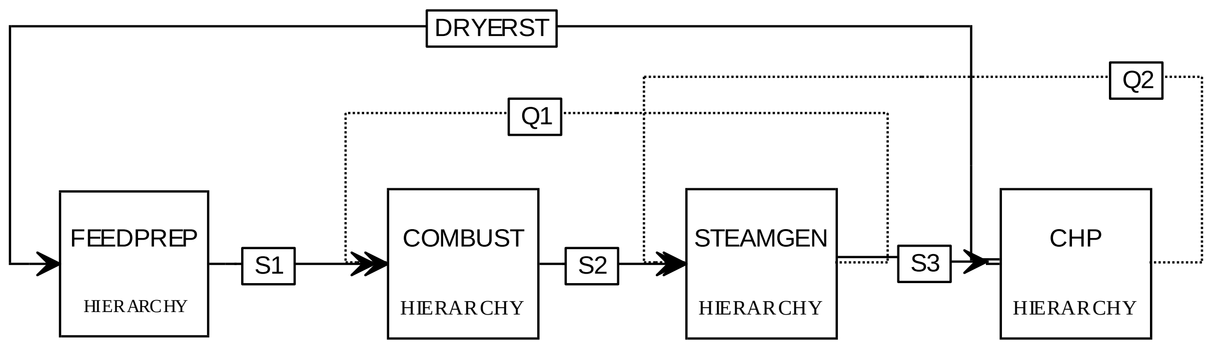
CHP HIERARCHY



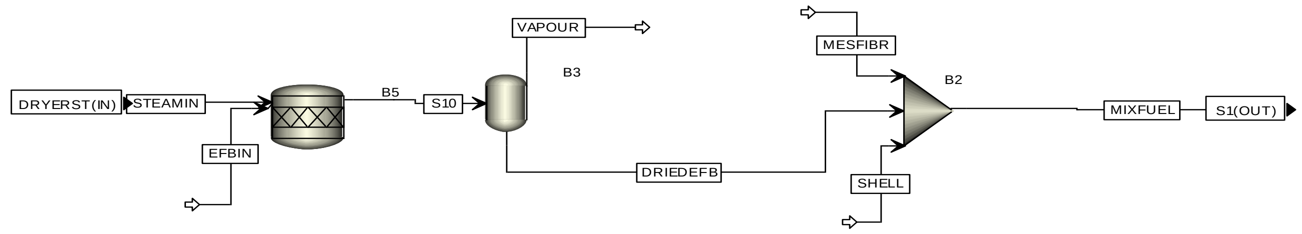
Gross Power (ELECOUT)	930	kW
Net Power	850	kW

	PRHOTWAT	PROCESST	S3	STEAMOUT	SUPH2OIN
Temperature C	223	223	80	223	400
Pressure bar	4	4	1	4	32
Vapor Frac	1	1	0	1	1
Mass Flow kg/hr					
H2O	4150	6525	4150	10675	10675

A2: Process flow diagram and stream data for CPO mill solid residue to in-house CHP (13 tons FFB/hr) theoretical scenario 2 (efb addition)

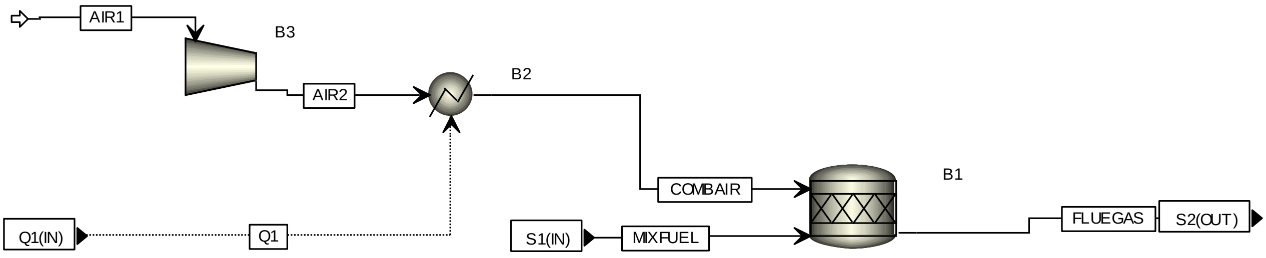


FEEDPREP HIERARCHY



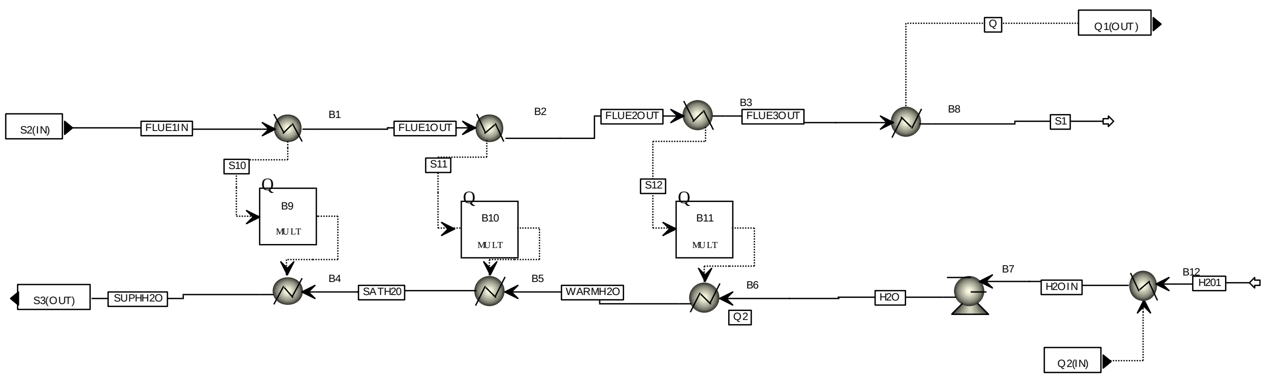
	DRIEDEFB	EFBIN	MESFIBR	MIXFUEL	S10	SHELL	STEAMIN	VAPOUR
Temperature C	60	25	25	225	110	25	223	60
Pressure bar	1	1	1	1	1	1	4	1
Vapor Frac	0	0	0	0	1	0	1	1
Mass Flow kg/hr								
H2O	0	0	0	0	22675	0	21651	22675
LIGNIN	693	925	392	1252	693	166	0	0
HEMICEL	1380	1841	526	2109	1380	202	0	0
CELLULOS	2989	3321	836	4371	2989	545	0	0

COMBUST HIERARCHY



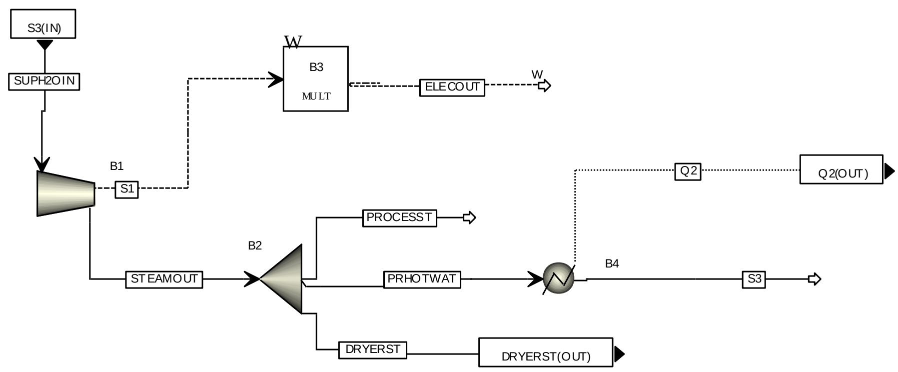
	AIR1	AIR2	COMBAIR	FLUEGAS	MIXFUEL
Temperature C	25	37	250	1647	225
Pressure bar	1	1.5	1.5	1	1
Vapor Frac	1	1	1	1	0
Mass Flow kg/hr					
N2	46858	46858	46858	46858	0
O2	14142	14142	14142	4175	0
H2O	0	0	0	4171	0
NO2	0	0	0	0	0
SO2	0	0	0	0	0
CO2	0	0	0	13527	0
LIGNIN	0	0	0	0	1252
HEMICEL	0	0	0	0	2109
CELLULOS	0	0	0	0	4371

STEAMGEN HIERARCHY



	FLUE1IN	FLUE1OUT	FLUE2OUT	FLUE3OUT	H2O	H2OIN	S1	SATH20	SUPHH2O	WARMH2O
Temperature C	1647	1000	600	350	34	34	120	243	400	155
Pressure bar	1	1	1	1	25	1	1	35	32	35
Vapor Frac	1	1	1	1	0	0	1	0	1	0
Mass Flow kg/hr										
N2	46858	46858	46858	46858	0	0	46858	0	0	0
O2	4175	4175	4175	4175	0	0	4175	0	0	0
H2O	4171	4171	4171	4171	31261	31261	4171	31261	31261	31261
NO2	0	0	0	0	0	0	0	0	0	0
SO2	0	0	0	0	0	0	0	0	0	0
CO2	13527	13527	13527	13527	0	0	13527	0	0	0

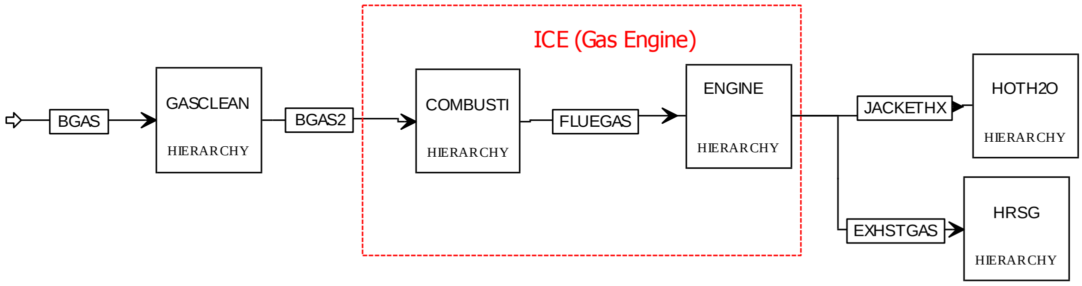
CHP HIERARCHY



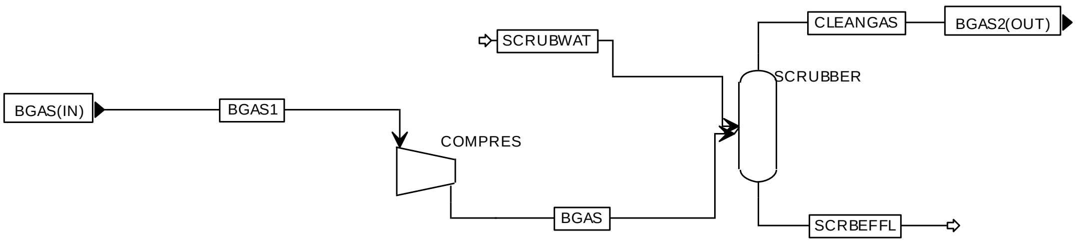
Gross Power (ELECOUT)	2700	kW
Net Power	2500	kW

	DRYERST	PRHOTWAT	PROCESST	S3	STEAMOUT	SUPH2OIN
Temperature C	223	223	223	80	223	400
Pressure bar	4	4	4	1	4	32
Vapor Frac	1	1	1	0	1	1
Mass Flow kg/hr						
H2O	21651	4150	5460	4150	31261	31261

A3: Process flow diagram and stream data for POME-biogas to in-house CHP (13 tons FFB/hr facility) theoretical Gas-engine route

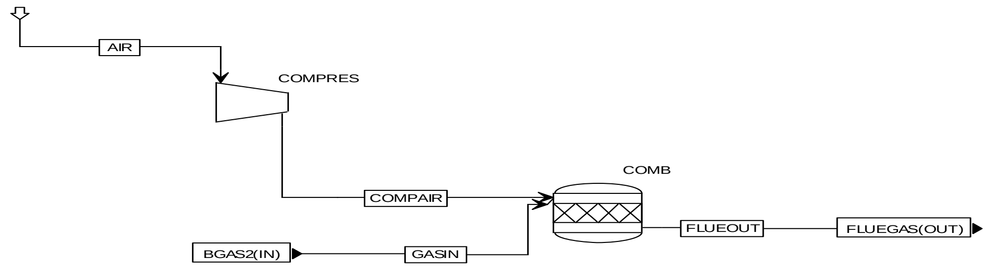


GASCLEAN HIERARCHY



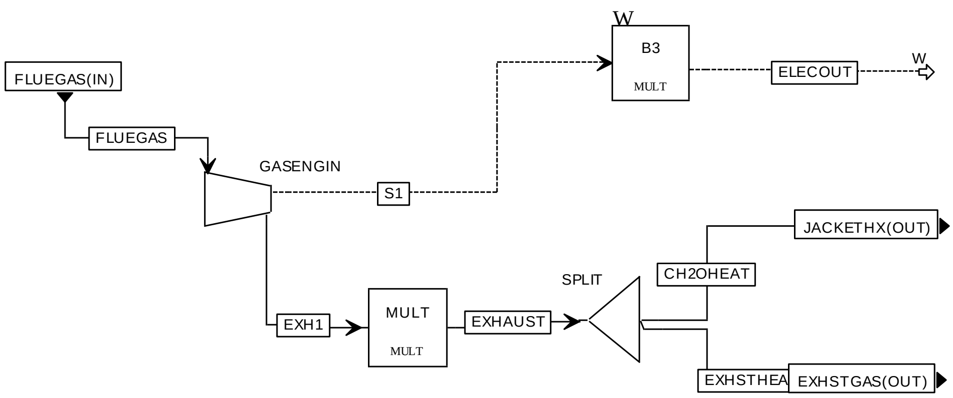
	BGAS	BGAS1	CLEANGAS	SCRBEFFL	SCRUBWAT
	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID
Temperature C	202	55	34	17	35
Pressure bar	4	1	1	1	1
Vapor Frac	1	1	1	0	0
Mass Flow kg/hr					
H_2O	0	0	7	361	367
CH_4	116	116	113	3	0
CO_2	171	171	35	137	0
H_2S	1	1	0	1	0

COMBUSTI HIERARCHY



	AIR	COMPAIR	FLUEOUT	GASIN
Temperature C	25	221	1860	34
Pressure bar	1	4	4	1
Vapor Frac	1	1	1	1
Mass Flow kg/hr				
H2O	0	0	261	7
CH4	0	0	0	113
CO2	0	0	346	35
H2S	0	0	0	0
O2	453	453	0	0
N2	1500	1500	1500	0

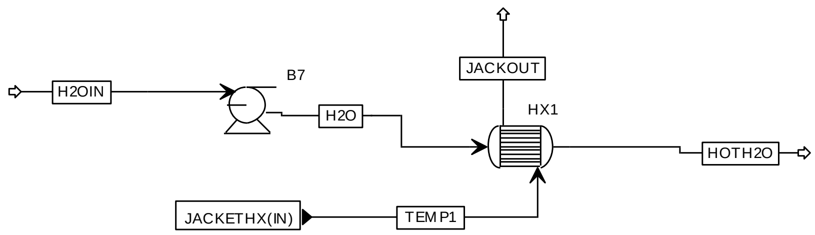
ENGINE HIERARCHY



Gross Power (ELECOUT)	590	kW
Net Power	385	kW

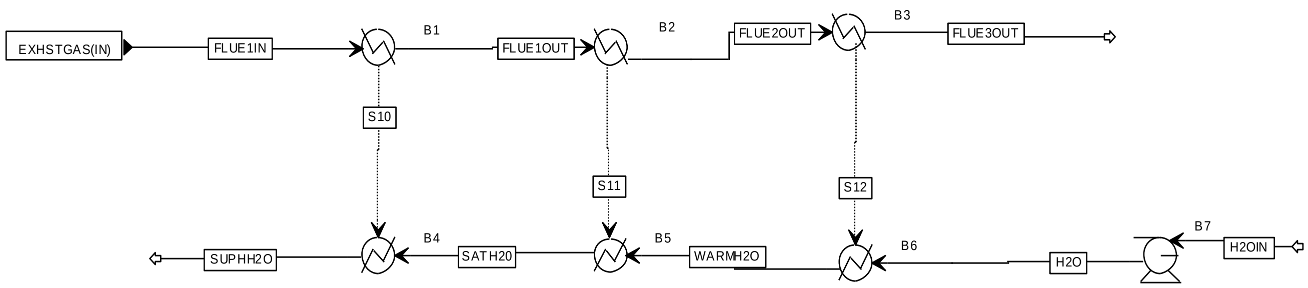
	CH2OHEAT	EXH1	EXHAUST	EXHSTHEA	FLUEGAS
Temperature C	1447	1447	1447	1447	1860
Pressure bar	1	1	1	1	4
Vapor Frac	1	1	1	1	1
Mass Flow kg/hr					
H2O	74	261	147	74	261
CH4	0	0	0	0	0
CO2	97	346	195	97	346
H2S	0	0	0	0	0
ACETO-01	0	0	0	0	0
O2	0	0	0	0	0
N2	422	1500	845	422	1500

HOTH20 HIERARCHY



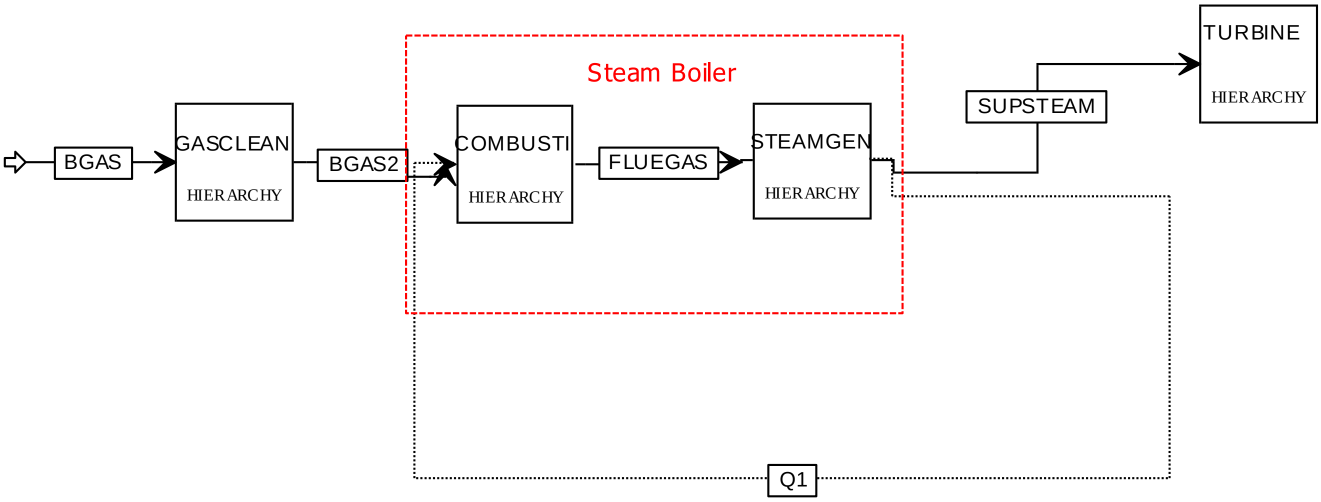
	H2O	H2OIN	HOTH2O	JACKOUT	TEMP1
Temperature C	25	25	80	222	1447
Pressure bar	3	1	3	1.3	1.3
Vapor Frac	0	0	0	1	1
Mass Flow kg/hr					
H2O	4150	4150	4150	74	74
CO2	0	0	0	97	97
H2S	0	0	0	0	0
ACETO-01	0	0	0	0	0
O2	0	0	0	0	0
N2	0	0	0	422	422

HRSG HIERARCHY

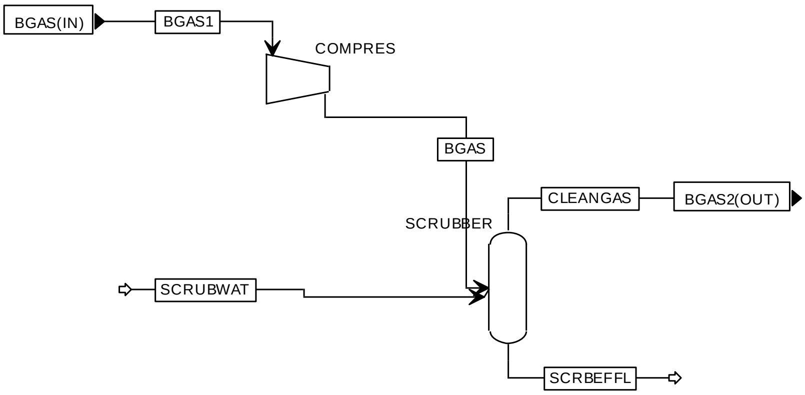


	FLUE1IN	FLUE1OUT	FLUE2OUT	FLUE3OUT	H2O	H2OIN	SATH20	SUPHH2O	WARMH2O
Temperature C	1447	800	600	350	25	25	128	186	128
Pressure bar	0	1	1	1	3	1	3	4	3
Vapor Frac	1	1	1	1	0	0	0	1	0
Mass Flow kg/hr									
H2O	74	74	74	74	320	320	320	320	320
CH4	0	0	0	0	0	0	0	0	0
CO2	97	97	97	97	0	0	0	0	0
H2S	0	0	0	0	0	0	0	0	0
ACETO-01	0	0	0	0	0	0	0	0	0
O2	0	0	0	0	0	0	0	0	0
N2	422	422	422	422	0	0	0	0	0

A4: Process flow diagram and stream data for POME to in-house CHP (13 tons FFB/hr facility) theoretical Steam boiler/turbine route

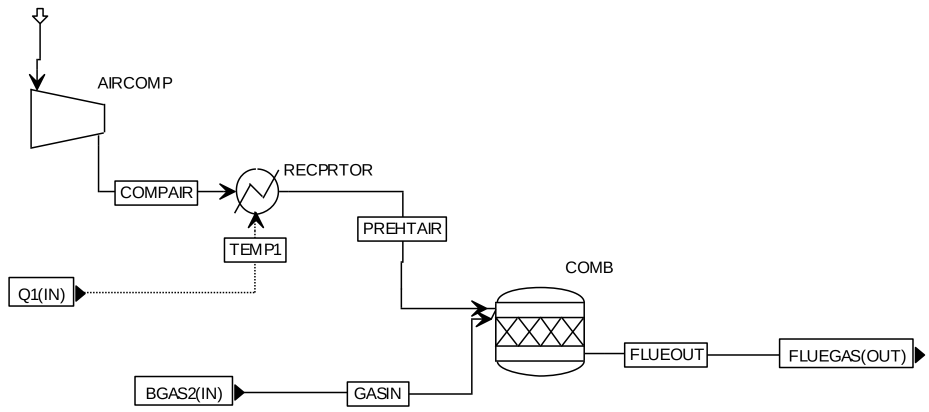


GASCLEAN HIERARCHY



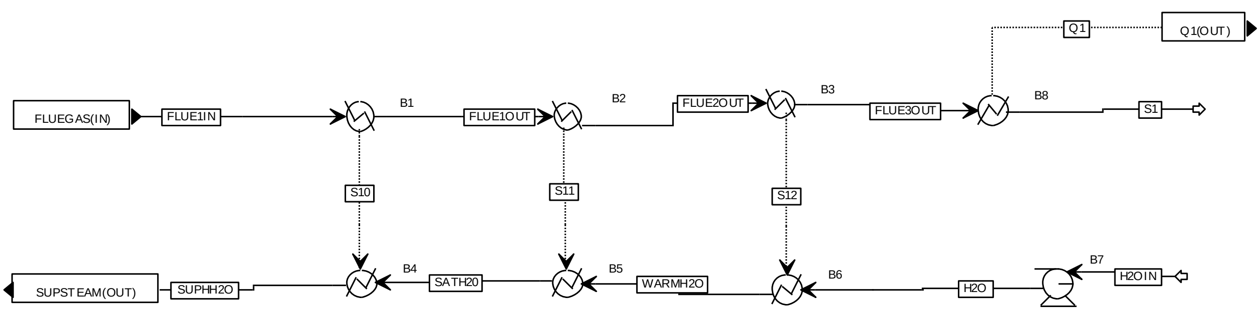
	BGAS	BGAS1	CLEANGAS	SCRBEFFL	SCRUBWAT
	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID
Temperature C	202	55	34	23	35
Pressure (bar)	4	1	1	1	1
Vapor Frac	1	1	1	0	0
Mass Flow kg/hr					
H2O	0	0	7	361	367
CH4	116	116	113	3	0
CO2	171	171	35	137	0
H2S	1	1	0	1	0

COMBUSTI HIERARCHY



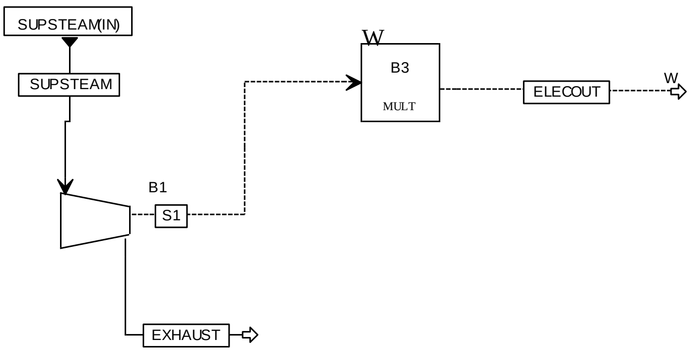
	AIR	COMPAIR	FLUEOUT	GASIN	PREHTAIR
Temperature C	25	93	1757	34	212
Pressure bar	1	2	4	1	1
Vapor Frac	1	1	1	1	1
Mass Flow kg/hr					
H2O	0	0	261	7	0
CH4	0	0	0	113	0
CO2	0	0	346	35	0
H2S	0	0	0	0	0
ACETO-01	0	0	0	0	0
O2	603	603	150	0	603
N2	1997	1997	1997	0	1997

STEAMGEN HIERARCHY



	FLUE1IN	FLUE1OUT	FLUE2OUT	FLUE3OUT	H2O	H2OIN	S1	SATH20	SUPHH2O	WARMH2O
Temperature C	1757	1000	600	350	26	25	250	243	400	140
Pressure bar	4	1	1	1	35	1	1	35	32	35
Vapor Frac	1	1	1	1	0	0	1	0	1	0
Mass Flow kg/hr										
H2O	261	261	261	261	1631	1631	261	1631	1631	1631
CO2	346	346	346	346	0	0	346	0	0	0
H2S	0	0	0	0	0	0	0	0	0	0
O2	150	150	150	150	0	0	150	0	0	0
N2	1997	1997	1997	1997	0	0	1997	0	0	0

TURBINE HIERARCHY



Gross Power (ELECOUT)	160	kW
Net Power	50	kW

	EXHAUST	SUPSTEAM
Temperature C	216	400
Pressure bar	4	32
Vapor Frac	1	1
Mass Flow kg/hr		
H2O	1630	1630

APPENDIX B: ADDITIONAL INFORMATIONS ON ECONOMIC ASSESSMENTS

B1: VacVina digester materials and component data (from CCRD/VACVINA, 2004) adopted in digester cost estimations for AD of cassava peels/cattle dung process

		7 m^3 digester		300 m^3 digester		512 m^3 digester	
Material	Unit	Cost/unit	Quantity	Quantity	Cost	Quantity	Cost
standard solid brick	pieces	0.2	1400	48600	11421	108600	25521
Cement	Kg	0.2	600	20829	3887	46543	8685
Coarse sand	m^3	31.4	1.5	52	1634	116	3650
Gravel	m^3	52.3	0.5	17	908	39	2028
iron bars (Φ 8 mm)	Kg	0.4	30	1041	381	2327	851
Zinc joint pipe	piece	10.2	1	35	356	78	794
PVC pipe (Φ 21 mm)	m	0.8	4	139	107	310	239
Valve, joints	piece	10.0	15	521	5197	1164	11612
Plastic pipe(Φ 21 mm)	m	0.8	15	521	402	1164	897
PVC (Φ 110 mm)	m	4.1	1	35	141	78	316
Workmanship (10%)					2443		5459
TOTAL					**26875**		**60054**

B2: The Gasification power system's equipment cost estimation for the large scale (mechanised CF mill's in-house energy generation) facility (Adapted from Serpagli et al., 2010b).

Components of gasification power system	Quantity	Cost 2010 ($)	stream name	Scale value (Serpagli et al., 2010)	Scale value this project	Scaling exponent	size ratio	scaled purchase 2010 ($)	Purchased cost 2014 ($)
'Ankur' Biomass Gasifier Model WBG-200 in Ultra Clean Gas Mode (including necessary accessories and auxilliaries)	1	76588	Gross power (kW)	120	57	0.6	0	48775	49830
Cummins GTA-855-G engine (modified to work on Producer Gas) with a Gross output of 120 kWe on producer gas in the grid connected mode	1	65509	Gross power (kW)	120	57	0.6	0	41720	42622
Manually controlled Producer Gas Burner	1	1649	syngas(m^3/hr)	500	287	0.6	1	1182	1207
Parallel line of filters for continuous operation	1 set	6485	syngas(m^3/hr)	500	287	0.6	1	4647	4748
Gasifier Cooling Tower	lump sum	5496	syngas(m^3/hr)	500	287	0.8	1	3524	3601
Engine Cooling Tower	1	5825	producer gas(m^3/hr)	500	287	0.8	1	3735	3816
Skip Charger with double feed door assembly for feeding raw materials to the gasifier (from ground level to the gasifier feed door)	1	8024	Biomass feedrate(kg/hr)	200	115	0.6	1	5750	5874
Moisture Meter	1	176	constant (gasifier feed mc)	20	20	0.6	1	176	180
Biomass Drying Arrangement (Based on engine Exhaust)	1	8024	Biomass feedrate(kg/hr)	200	115	0.6	1	5750	5874
Dry Ash Char Removal System (Actual handling of ash/char from gasifier area to final disposal/storage point will be in customer's scope)	lump sum	6485	Char produced(kg/hr)	20	5	0.6	0	2682	2740
Gas Cooler (M.S. Construction)	1	3957	syngas(m^3/hr)	500	287	0.8	1	2537	2592
7 TR Chiller	1	7694	syngas(m^3/hr)	500	287	0.8	1	4934	5041
Water Treatment Plant	lump sum	7694	syngas(m^3/hr)	500	287	0.6	1	5514	5633
Platform, Ladder for the gasifier	1 set	2748	Gross power (kW)	120	57	0.6	0	1750	1788
Biomass Dryer	1	9892	Biomass feedrate(kg/hr)	200	115	0.6	1	7089	7242
HAG for Flesh dryer	1	16487	Cassava grits (kg/day)	7000	6776	0.6	1	16168	16518
Electric generator 30kWh with diesel tank	1	19785		1	1		1	19785	20213
Grid for public distribution system	lump sum	12310						12310	12576
Spare parts, lubricating oils, filters for 2 operations years	lump sum	4397	Gross power (kW)	120	57	0.6	0	2800	2861
Packing Charges for the system	lump sum	4397	Gross power (kW)	120	57	0.6	0	2800	2861
Transportation/assembling/commisisoning	lump sum	26379	Gross power (kW)	120	57		0	26379	26949
Total delivered/installed cost									224764

B3: Economic and technical parameters for the modelled BCST process

Parameter	Scenario 1	Scenario 2
Annual net electricity generated (MW)	6360	18700
Plant life (yrs)	25	25
TCI (million $)	18.00	36.60
TOC (million $/yr)	2.57	4.91
Feedstock cost ($/kg)[1]		
mf	0.091	0.091
pks	0.157	0.157
efb	0.051	0.051
Revenue		
Base-case electricity selling price ($/kWh)[2]	0.207, 0.348	0.207, 0.348
Process steam selling price ($/kg)[3]	0.04	0.04
Process hot water selling price ($/kg)[3]	0.013	0.013
Technical performance		
Overall CHP efficiency (%)	70.2	68.6

[1] Estimated as equal to the price of firewood on an energy basis, which is $0.138/kg at LHV of 15 MJ/kg. Thus on an energy basis translates to $0.01/MJ (Energica, 2009)
[2] Since the bioelectricity generated will be substituting electricity from the national grid, it is assumed the cost of electricity is in the range of quoted Non-residential/Commercial tariff of $0.2073 (between 0-100 kWh) and $0.348 (above 600 kWh) from the Public Utility Regulation Commission (PURC, 2014).
[3] Estimated as sum of costs of required biomass fuel and water (Commercial/Industrial quote of $0.00092/kg; PURC, 2014), boiler house labour + depreciation ($0.00272/kg) and a profit margin of 10 %.

B4: Economic and technical parameters for the POME-biogas CHP process

Parameter	Gas-engine route	Steam turbine route
Annual net electricity generated (MW)[1]	2770	370
Plant life (yrs)	15	15
TCI (million $)[2]	5.77	8.23
TOC (thousand $/yr)[3]	277.00	319.62
Revenue		
Base-case electricity selling price ($/kWh)[4]	0.207, 0.348	0.207, 0.348
Process steam selling price ($/kg)[5]	0.066	0.076
Process hot water selling price ($/kg)[5]	0.009	-
Land application benefit ($/yr)[6]	6000	6000

[1] The net electricity available for export or sale is the gross electricity minus the sum of electric power requirement for the biogas generation, biogas scrubbing, CHP processes and land application facility.
[2] Includes capital costs of anaerobic digestion, biogas cleaning, CHP and Land application (digester effluent as a fertilizer application) stations
[3] Includes total operating cost of anaerobic digester, biogas cleaning, CHP and land application facilities. Estimates based on study of Yeoh, 2003.
[4] Since the bioelectricity generated will be substituting electricity from the national grid, it is assumed the cost of electricity is in the range of quoted Non-residential/Commercial tariff of $0.2073 (between 0-100 kWh) and $0.348 (above 600 kWh) from the Public Utility Regulation Commission (PURC, 2014).
[5] Estimated as sum of costs of required biogas fuel (As most thermal power plants in Ghana are fuelled by diesel, biogas cost was assumed to be equal to the cost of diesel on energy basis, which is $1.002/litre at 35.8 MJ/Litre translating to $0.028/MJ) and water (Commercial/Industrial quote of $0.00092/kg; PURC, 2014), boiler house labour + depreciation ($0.00272/kg) and a profit margin of 10 %.
[6] Considering the digested POME effluent is applied as an organic fertiliser, the benefit was estimated as the selling price of increased FFB yield which was based on 10% increase in FFB yield for POME load of 345tons/day on a 138.98ha. Hence the 181.85 tons/day POME is proportional to a farm size of 73.25 ha (Yeoh, 2004). It was assumed FFB yield was 20.08 tons/ha (Yusoff, 2006). The selling price of FFB was $ 40.87/ton obtained from local suppliers as at 21st September, 2014.

B5: Economic and technical parameters for the cassava peels/cattle dung AD to power/biogas process

Parameter	Semi-mechanised CF AD facility	Mechanised CF AD facility
Gross power generated (kW)	100	230
Net electric power (kW) [1]	90	210
Plant life (yrs)	15	15
TCI ($)	531800	932700
TOC ($/yr)	67800	84300
Feedstock cost ($/yr)		
Cassava peels [2]	4290	9680
Cattle dung [2]	4290	9680
Revenue		
Baseline electricity selling price ($/kWh)[3]	0.207, 0.348	0.207, 0.348
Cassava meal dryer's biogas ($/yr) [4]	20360	41050
Digestate (biofertiliser) ($/yr) [5]	9680	42980

[1] Net electric power was determined as: Gross power - (power required in biogas generation, cleaning & storage + power required in electric power generation).
[2] In its appraisal, the feedstock (cassava peels and cattle dung) was assumed to be obtained and transported to the biogas facility at a delivered cost of $10 /ton (Serpagli et al, 2010).
[3] Since the bioelectricity generated will be substituting electricity from the national grid, it is assumed the cost of electricity is in the range of quoted Non-residential/Commercial tariff of $0.2073 (between 0-100 kWh) and $0.348 (above 600 kWh) from the Public Utility Regulation Commission (PURC, 2014).
[4] As the generated biogas will be substituting diesel as dryer fuel in the CF process, its estimated price was based on cost of diesel on energy basis, which is $1.002/litre at 35.8 MJ/Litre translating to $0.028/MJ. Hence biogas at LHV of 24 MJ/m^3 (Yeoh, 2004) gives an estimated price of $0.672/$m^3$.
[5] Based on estimated price of $18/ton digestate (See Section 5.2.3.1 for details on digestate appraisal).

B6: Technical and economic parameters for the cassava peels/wood shavings/sawdust gasification process

Parameter	Semi-mechanised CF gasification facility	Mechanised CF gasification facility
Gross power generated (kW) [1]	18	57
Net electric power (kW) [1]	15	47
Plant life (yrs)	15	15
TCI (thousand $)	338.0	461.0
TOC (thousand $/yr)	84.5	94.0
Feedstock cost ($/yr)		
Cassava peels [2]	4347	9800
Wood shavings/sawdust [2]	2110	4760
Revenue		
Base electricity selling price ($/kWh)[3]	0.207, 0.348	0.207, 0.348
Syngas (fuelling cassava meal dryer) ($/yr) [4]	20360	41050
Char ($/yr) [5]	7070	15950

[1] Estimates adapted from gasification of same feedstock-mix (cassava peels to wood shavings/sawdust at 1:1 proportion with wood shavings and sawdust at 7:3 proportions) yielding 500 m^3 syngas/200kg biomass mix (at calorific value of 4605.48 kJ/m^3) generating 120kW and 100kW gross and net electricity respectively (Serpagli et al., 2010b).
[2] In its appraisal, the feedstock (cassava peels, wood shavings and sawdust) was assumed to be obtained and transported to the gasification power facility at a delivered cost of $10/ton (Serpagli et al, 2010a).
[3] Since the bioelectricity generated will be substituting electricity from the national grid, it is assumed the cost of electricity is in the range of quoted Non-residential/Commercial tariff of $0.207 (between 0-100 kWh) and $0.348 (above 600 kWh) from the Public Utility Regulation Commission (PURC, 2014).
[4] Considering the generated syngas will be replacing diesel as dryer fuel in the CF process, its estimated price was based on cost of diesel on energy basis, which is $1.002/litre at 35.8 MJ/Litre translating to $0.028/MJ. Hence syngas at 4.605 MJ/m^3 (Serpagli et al., 2010b) estimated price of $ 0.129/m^3.
[5] Estimated based on char yield of 4% of biomass fed to gasifier (Serpagli et al., 2010b) and price of charcoal at $1.04/kg in 2009 translating to $0.478/kg in 2014 (Energica, 2009).

B7: Economic parameters for the modelled food processes

Crude Palm Oil

Parameter	Traditional		Semi-Mechanised		Mechanised	
	B/C	I/C	B/C	I/C	B/C	I/C
Capacity (tons CPO/yr)	25	25	275	417	21440	21440
Plant life (yrs)	5	5	10	10	15	15
Expenditure						
FFB ($/yr) [a]	6155	6155	85200	85200	3989300	3989300
Transportation of FFB ($/yr) [b]	2390	2390	33080	33080	1548100	1548100
TCI($)	5250	4470	53390	56213	17042260	17746000
TPC ($/yr)	29932	25200	277600	284560	7811200	10865000
Revenue($/yr)						
CPO [c]	17940	17940	195500	296200	15225600	15225600
Nuts [c]	2740	2740	66130	66130	-	-
mf [d]	1850	-	-	-	523300	1200200
pks [d]	-	-	-	-	532800	1078500
efb [d]	3050	2230	4100	24050	2028400	2312500
Kernels [c]	-	-	-	-	976900	976900

[a] The fresh fruit bunch (FFB) price was estimated based on the price of $41/ton provided by local suppliers in Ghana as at 3rd September, 2014.
[b] The cost of transporting the FFB to the CPO mills was estimated based on the study of Adjei-Nsiah et al. (2012) to be $15.86/ton FFB.
[c] Estimated from prices provided by local suppliers in Ghana as at 3rd September, 2014 (CPO-$710/ton, nuts-$104.6/ton and kernels-$75/ton).
[d] Estimated as equal to the price of firewood on an energy basis, which is $0.138/kg at LHV of 15 MJ/kg. Thus on an energy basis translates to $0.01/MJ (Energica, 2009).

Cassava Flour

Parameters	Traditional		Semi-Mechanised		Mechanised (Grating route)		Mechanised (Chipping route)	
	B/C	I/C	B/C	I/C	B/C	I/C	B/C	I/C
Capacity (tons CF/yr)	6	10	270	270	562	562	562	561
Plant life (yrs)	5	5	10	10	10	10	10	10
Expenditure								
Cassava ($/yr) [a]	1545	2648	96510	96510	200800	200800	200800	200800
Transportation of Cassava ($/yr) [b]	276	474	1395	1395	2902	2902	2902	2902
TCI($)	1150	1440	46050	52330	174860	171640	325130	333900
TPC ($/yr)	3015	5180	162220	163880	363390	345880	387940	440500
Revenue($/yr)								
Cassava flour [c]	3420	5530	151200	151200	314500	314500	419330	419330

[a] The cassava feedstock was assumed to be obtained from a household's farm for processing whiles in the case of the semi-mechanised and mechanised processes, it was assumed to be purchased from neighbouring farmers. Hence its price was based on average farm gate price of $64.36/ton as at January, 2014 (obtained from local producers).
[b] Estimated as the average weight equivalent cost of transportation of maize from rural areas to urban centres at $0.12/ton per km (The World Bank, 2012). It was assumed raw materials are mobilised within a vicinity of 7.5 km radius (Rabirou et al., 2012) from the CF processing facility. The cost of transportation was consequently $0.91/ton (The World Bank, 2012).
[c] Given the ultimate uses of the Cassava flour is as wheat flour substitute in baking among others, its selling price was estimated as equivalent value of wheat flour on mass basis, which is at average selling price of $560/ton obtained from field quote as at September, 2014).

Maize Flour

Parameters	Traditional B/C	Traditional I/C	Semi-Mechanised B/C	Semi-Mechanised I/C	Mechanised B/C	Mechanised I/C
Production Capacity (tons MF/yr)	1.6	1.8	227	324	1551	1551
Plant life (yrs)	5	5	10	10	10	10
Expenditure						
Maize grains ($/yr)	360[a]	360[a]	191700[b]	82150[a]	920320[b]	394300[a]
Transportation of grains ($/yr)[c]	2	2	450	450	2150	2150
Cobs taken to MF facility ($/yr)	-	-	-	50370	-	8390
Transportation of cobs ($/yr)[c]	-	-	-	291	-	48
TCI($)	485	620	51070	44950	262850	184080
TPC ($/yr)	1269	1286	233942	197248	1140400	655970
Revenue($/yr)						
Maize flour [d]	653	742	181637	181637	868720	868720
Bran [e]	29	33	22750	22750	115760	115760

[a] The maize grains are obtained from an individual's own farm in the case of traditional or bought from farm gates in the case of semi-mechanised/mechanised levels. Hence estimated maize price was based on Ministry of Food and Agriculture's (MOFA) recommended farm gate price of $133.14/ton in 2012 adjusted to $170.6/ton in 2014 (Ministry of Food and Agriculture, Republic of Ghana (MOFA). Available at http://mofa.gov.gh/site/?page_id=11395, Accessed on 12 September, 2014).
[b] Shelled maize are purchased from Licensed Buying Companies at a MOFA recommended price of $207.1/ton in 2012 adjusted to $398.2/ton in 2014 (Ministry of Food and Agriculture, Republic of Ghana (MOFA). Available at http://mofa.gov.gh/site/?page_id=11395, Accessed on 12 September, 2014).
[c] Estimated as the weight equivalent cost of transportation of maize from rural areas to urban centres at $0.12/ton per km (The World Bank, 2012). It was assumed raw materials are mobilised within a vicinity of 7.5 km (Rabirou et al., 2012) radius from the MF processing facility. The cost of transportation was consequently $0.91/ton.
[d] Given the ultimate uses of the maize flour is as wheat flour substitute, its selling price was estimated as equivalent value of wheat flour on mass basis, which is at average selling price of $560/ton (field quote as at September, 2014). However, for the traditional flour, the price was estimated as ¾ of the aforementioned price due to its anticipated low quality compared to the flour from the semi-mechanised and mechanised processes.
[e] Given the intended use of generated bran is as poultry feed due to its germ fraction being rich in protein and oils, its price was assumed to be half the price of poultry feed on mass basis, which is $600/ton obtained from field quote as at September, 2014.

B8: Main assumptions in estimating the total capital investment (TCI) for the energy facilities

Economic parameters	Energy facilities
Total direct cost (TDC)	117.5% of total installed equipment cost [1]
Total indirect cost (TIC)	50% of TDC [1,2] + contingency (10% of TDC) [1]
Fixed capital investment (FCI)	TDC + TIC + land [2]
Working capital (WC)	5% of FCI [1]

[1] Humbird et al., 2011; [2] Peters and Timmerhaus, 2003