SYSTEMS APPROACH IN DEVELOPING A MODEL FOR SUSTAINABLE PRODUCTION OF BIOENERGY IN MALAWI

By

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Declaration

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This dissertation includes ***two*** original papers published in peer reviewed journals and **one** unpublished publication. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

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Abstract

Bioenergy production from primary forest and rice residues can contribute to modern energy supply, such as electricity, liquid biofuels and gas, to rural communities in Malawi. These bioresources can be utilised for bioenergy production without alienating land from cultivation of other crops. However, sustainability of forest and rice residues-based bioenergy systems is complex owing to the dependency of availability of the residues on timber and rice production. Alterations in process operations in timber and rice production systems can cause variations in production and supply of the residues to a bioenergy conversion plant over time. For instance, forest management systems have evolved from sustainable yield management, which promotes clear cutting of mature forest stand to maximise the yield of wood products to sustainable forest management that promotes partial harvesting of mature forest stand to allow for ecosystem balance. Switching the harvesting regimes from clear cut to partial harvesting of mature forest stand, can influence variation in yield of forest residues in forest plantations over time. Variations are also evident in rice residues production and supply chains, emanating from seasonal production of rice and demand of the rice residues for competing uses. Stability in production and supply of the residues over a long time horizon can promote availability of the residues-based bioenergy systems and reliability of bioenergy supply to end use processes over time. Systems approach modelling based on systems thinking and system dynamics modelling methodology, was used in this study to develop a model for sustainable production of bioenergy (SAS-Biopro model). The model demonstrates state limiting processes to resilience of primary forest and rice residues supply chains for bioenergy production. Simulation results of the model show that variations in primary forest residues value chain over time result from variations in stocks of mature stand caused by over-exploitation for timber production, delayed replanting, high death (mortality) rate of replanted trees and underinvestment in plantations management. Results from scenario testing show that an integrated framework for forest plantations management and forest residues-based bioenergy production, can promote synchronised operation and management of the forest plantations and bioenergy production as a unit (whole) system. The framework entails setting an annual allowable cut for harvesting mature forest stand, synchronizing harvesting and replanting 100% of the annual allowable cut immediately after harvesting, reducing tree mortality fraction to less than 0.1, and sizing the scale of operation of bioenergy conversion plants based on the amount of

residues generated from the annual allowable cut. The framework can promote stability of residues production and supply to bioenergy conversion plants. Similarly, modelling sustainability of rice residues-based bioenergy production has shown that a synergetic integration of bioenergy and rice production can simultaneously increase bioenergy and rice production over time. Thus, synergetic integration of bioenergy and rice production can promote stability, availability and reliability of rice (food) and rice residues supply for bioenergy production. This research has filled a significant gap in strategic information such as dynamics in residues-based bioresource flow and consumption rates that create a transient state, which can guide formulation of strategies for synchronising the scale of operation of the residues-based bioenergy conversion plants and operation processes in the primary systems that generate the residues. The research outputs provide innovative whole systems and synergetic integration, for production and deployment of residues-based bioenergy, to promote resilience of the residues supply chains to bioenergy conversion plants. These concepts can promote uptake and diffusion of small-scale bioenergy conversion technologies in primary systems that generate the residues. Matching the scale and rate of operation of the bioenergy conversion plants with the annual rate of production of the residues can provide opportunity for incremental uptake of small-scale residues-based bioenergy systems. Therefore, the concepts, although approached from the technology and process point of view, are flexible to respond to policy and societal changes in the value chain of bioenergy production. The concepts can be adopted in forest plantations and rice farms management systems to promote sustainability of bioenergy production from forest and rice residues.

Opsomming

Die produksie van bio-energie uit primêre bos- en rys-afvalprodukte kan ’n bydrae lewer tot huidige energie-behoeftes soos met die verskaffing van elektrisiteit, vloeibare biobrandstowwe en gas aan landelike gemeenskappe in Malawi. Hierdie biobronne kan aangewend word vir bio-energie-produksie sonder om grond vir die verbouing van ander gewasse te vervreem. Die volhoubaarheid van bio-energie-stelsels gebaseer op bos- en rys-afvalprodukte is egter kompleks vanweë sy afhanklikheid van die beskikbaarheid van sodanige afvalprodukte. Oor tyd heen kan veranderings in proseswerksaamhede van hout- en rysproduksie-stelsels variasies in produksie en verskaffing van afvalprodukte aan bio-energie-verwerkingsaanlegte veroorsaak. Bosbestuurstelsels het byvoorbeeld ontwikkel uit volhoubare opbrengsbestuur, wat die kaalkap van volgroeide bosopstand bevorder om die opbrengs van houtprodukte vir volhoubare bosbestuur te maksimeer; hierdie bestuur laat toe dat gedeeltelike oes van volgroeide bosopstand bevorder word vir balans in die ekosisteem. Deur die oes-werkswyse te verander van kaalkap tot gedeeltelike oes van volgroeide bosopstand kan oor tyd heen opbrengsvariasie van bosafvalprodukte uit plantasies beïnvloed. Variasie is ook sigbaar in die produksie van rys-afvalprodukte en verskaffingskettings geassosieer met seisoenale produksie van rys en die kompeterende aanvraag na rysafvalprodukte. Oor ’n lang tydperk kan stabiliteit in produksie en verskaffing van afvalprodukte die beskikbaarheid van afvalprodukgebaseerde bio-energie-stelsels en die betroubaarheid van bio-energie-verskaffing aan eindgebruiksprosesse bevorder. Stelselbenaderingsmodellering gebaseer op stelseldenke en stelseldinamiese modelleringsmetodologie is in hierdie studie gebruik om ’n model (die SAS-Biopro-model) vir die volhoubare produksie van bio-energie te ontwikkel. Hierdie model demonstreer beperkings van prosesse deur die owerheid vir die lewensvatbaarheid van verskaffingskettings ten opsigte van primêre bos- en rysafvalprodukte vir bio-energie-produksie. Simulasie-uitslae van die model wys dat variasie in die primêre bosafvalprodukte-waardeketting oor tyd ontstaan as gevolg van variasie in onderstamme van volgroeide opstand veroorsaak deur oorbenutting vir houtproduksie, uitgestelde herplanting, hoë koers van vrekte onder herplantings en onderinvestering in plantasiebestuur. Uitslae van scenario-toetse wys dat ’n geïntegreerde raamwerk vir bosbestuur en bio-energie-produksie stabiliteit in die produksie en verskaffing van afvalprodukte aan ’n bio-energie-verwerkingsaanleg kan bevorder deur sinkronisasie van die oes van volgroeide bosopstand vir houtproduksie en herplant van die geoeste dele, die

instelling van drempelwaardes vir die oes van volgroeide bosopstande per jaar, en die afparing van grootte en skaal van die bio-energie-verwerkingsaanleg se werksaamhede met afvalprodukte gegenereer uit die geoeste drempelwaardes as ’n volledige stelsel. Ingelyks, wys die modellering van die volhoubaarheid van rysafvalproduk-gebaseerde bio-energie-produksie dat ’n sinergistiese integrasie van bio-energie- en rys-produksie terselfdertyd beide met verloop van tyd kan verbeter. Dus kan die sinergistiese integrasie van bio-energie- en rysproduksie stabiliteit, beskikbaarheid en volhoubaarheid van rys (voedsel) sowel as rysafval vir bio-energie-produksie bevorder. Hierdie navorsing vul ’n beduidende gaping in strategiese inligting soos die dinamika van afvalgebaseerde bio-bronvloei en – verbruikerskoerse wat ’n kortstondige toestand veroorsaak en formulering van strategieë kan lei om die skaal van werksverrigting van afvalprodukgebaseerde bio-energie-verwerkingsaanlegte en prosesse in die primêre stelsels wat die afvalprodukte genereer te sinkroniseer. Die navorsingsuitsette verskaf innoverende volledige stelsels en sinergistiese integrasie vir produksie en aanwending van afvalprodukgebaseerde bio-energie, om lewensvatbaarheid van die afvalprodukverskaffingsketting vir bio-energie-verwerkingsaanlegte te bevorder. Sodanige konsepte kan die aanwending en verspreiding van kleinskaalse bio-energie-verwerkingstegnologieë bevorder in primêre stelsels wat die afvalprodukte genereer. Die afparing van skaal en werksverrigtingskoers van bio-energie-verwerkingsaanlegte met die jaarlikse produksiekoers van die afvalprodukte kan geleenthede verskaf vir toenemende aanwending van kleinskaalse afvalprodukgebaseerde bio-energiestelsels. Daarom is die konsepte buigsaam, alhoewel uit die tegnologie- en proses-oogpunt benader, om op veranderings in beleid en die samelewing te reageer in die waardeketting van bio-energieproduksie. Hierdie konsepte kan opgeneem word in bos- en ryslandbestuurstelsels om volhoubaarheid van bio-energieproduksie uit bos- en rysafvalprodukte te bevorder.

Dedication

I dedicate this work to my late parents, Lexon and Rute Chitawo, for their unwavering commitment to support my education despite enormous economic challenges they faced as peasant farmers, and to my dear wife Chimwemwe who has steadfastly supported me throughout this work.

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List of Acronyms

AAC	Annual allowable cut
agb	Above ground biomass
API	American Petroleum Industry
ASTM	American Standard Test Method
BAU	Business as usual
CBA	Cost-benefit analysis
DFC	Distance fixed cost
DoF	Department of Forestry
DSF	Decision support framework
DSS	Decision support system
DVC	Distance variable cost
EJ	Exajoules (10^{18} joules)
ESCOM	Electricity Supply Corporation of Malawi
GCOE	Generation cost of energy
GHG	Greenhouse gas
GWh	Giga watt hours
GIS	Geographical information systems
GoM	Government of Malawi
IAM	Integrated assessment modelling
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISA-AAC	Integrated system approach – annual allowable cut
MBEST	Malawi Biomass Energy Strategy
MCDA	Multi criteria decision analysis
MEDAR	Malawi Energy Demand Assessment Report
MEP	Malawi Energy Policy
MRASBDFS	Malawi Roadmap for Action towards Sustainable Bioenergy Development and Food Security
NPV	Net present value
LP	Linear Programming
Mboe	million barrels of oil equivalent
MERA	Malawi Energy Regulatory Authority

Mtoe	million tonnes of oil equivalent
rgf	Residues generation fraction
rrf	Replant removal flux
rrt	Replant removal time
RPR	Residues to product ratio
SA	Systems approach
SD	System dynamics
SFM	Sustainable forest management
SMFEs	Small and Medium Forestry Enterprises
SYM	Sustainable yield management
TDH	Total dynamic head
WBA	World Bioenergy Association

List of key publications

Journal papers

1. **Chitawo** M.L., Chimphango A.F.A. 2017. A synergetic integration of bioenergy and rice production in rice farms. Renewable and Sustainable Review, 75, 58-67.

2. **Chitawo** M.L. Chimphango A.F.A., Petersen S.O. 2018. Modelling sustainability of forest residues-based bioenergy system. Biomass and Bioenergy, 108, 90-100.

3. **Chitawo** M.L. Chimphango A.F.A. Sustainability of integrating bioenergy and timber production in forest plantations. (Manuscript submitted to the Journal of Energy).

Conference papers

1. [1]**Chitawo** M.L. Chimphango A.F.A., Petersen S.O. 2016. Systems approach model for sustainable production of bioenergy from primary forest residues from Viphya plantations in Malawi. 4th Annual System Dynamics Conference, 17th - 18th November, 2016, Stellenbosch, South Africa.

2. [2]**Chitawo** M.L. Chimphango A.F.A. 2016. A systems approach mapping of primary forest residues supply chain for sustainable production of bioenergy in Malawi. 2nd International Congress and Expo on Biofuels & Bioenergy, August 29-31, 2016, Sao Paulo, Brazil. Annual TAPPSA Conference, September 21-22, 2016, Durban, South Africa. Abstract available in a book of abstracts at: http://dx.doi.org/10.4172/2090-4541.C1.017 and on http://www.supergen-bioenergy.net/conference/abstracts

Poster presentation

1. **Chitawo** M.L. Chimphango A.F.A. Petersen S. 2017. Modelling sustainability of primary forest residues-based bioenergy system. Presented at the 60th World System Dynamics conference, Massachusetts, USA. Abstract available at http://www.systemdynamics.org/conferences/2017/proceed/index.html

[1] This paper received the Best Student Paper Presentation award sponsored by ESKOM South Africa
[2] This paper was presented at **two** conferences (in Brazil and South Africa)

2. Chimphango A.F.A., **Chitawo** M.L., Padi R.K. Sustainable integration of bioenergy and food systems that benefit the resource-poor in rural communities. Presented at the International Bioenergy Conference, March 22-23, 2017, SUPPERGEN Hub, Manchester, United Kingdom. Abstract available at: http://www.supergen-bioenergy.net/conference/posters-(41-62)/

Chapter 1: Introduction

1.1 Background

Bioenergy production from primary forest and rice residues can complement to or substitute for fossil fuels to meet macro and local energy needs. The production and utilisation processes of bioenergy are expected to contribute to social and economic development, reduction in greenhouse gas emissions, enhance energy access and security at local and national levels, given that the bioresources utilised for feedstock are locally produced and are renewable (Ackom et al., 2013). Bioenergy is produced from an array of feedstocks that include purposely grown energy crops, invasive terrestrial and aquatic plants, industrial and municipal wastes, agricultural and forest residues (Sims, 2002; Yamamoto et al., 2001). The contribution of forest and agricultural residues and wastes to the global energy mix has been projected to reach 33% of the commercial energy consumption of 1990 by the year 2100 (Yamamoto et al., 2001). However, despite the expected positive contribution of bioenergy from forest and agricultural residues, sustainability of residues-based bioenergy systems is complex owing to the dependency of availability of the residues on operational processes and policies governing the primary systems in which the residues are generated.

Availability of forest residues depends on operational processes and policies in timber or pulp production (Bolkesjø, et al., 2006). Krigstin et al., (2012) have reported that saw lumber production in Canada declined by 46.5% between 2004 and 2009. This implied a decline in production and availability of forest residues in Canada by the same margin over the same time horizon. In addition, development of sustainable supply chains of sawmill residues was affected by the lack of information related to quantity and quality of the residues within the same time frame (Krigstin et al., 2012). Thus, variations in timber or pulp production can result in variations in the amount of forest residues that can be collected and supplied to a bioenergy conversion plant for bioenergy production. Understanding the causal and effects of these variations over a long time horizon is essential for development of technological, process and policy innovations to promote availability and reliability of residues-based bioenergy systems. Variations in production and supply of feedstocks for bioenergy production can have impacts on availability, reliability and security of supply of bioenergy, which in turn can have significant implications on sustainability of the bioenergy production value chain.

1.2 Complexity of bioenergy production from forest and crop residues

Bioenergy production from residues-based bioresources is complex owing to many interconnected and interacting components and involvement of large number of stakeholders, from production of the feedstocks to energy supply to end use processes. Musango, (2012); Musango & Brent, (2011); Buchholz et al., (2007) have observed the complexity of bioenergy production as a technical, environmental, governance and social problem. The IPCC, (2011 Chap.2) highlights the importance of developing bioenergy systems that are economically viable, environmentally benign and socially acceptable so that bioenergy production and utilisation meets the global and local energy needs in a sustainable way.

Forest management systems for timber production that generate primary forest residues, and farm management systems for crop production that generate crop residues, involve many stakeholders, with different levels of interest and influence on decision making when implementing operational processes and policies in the systems. Figure 1.1 shows the interconnectedness of the components of a residues-based bioenergy. These components are in continuous interaction to achieve the design objective of the system. Undesirable performance and failure of the whole system can arise from poor performance or failure of any one of the interacting component (Musango, 2012; Musango & Brent 2011, Maani & Cavana, 2007).

In addition, a residues-based bioenergy system is interconnected and in continuous interaction with operational policies, regulations and practices that regulate the production of the principal products in the primary systems that generate the residues. The components of the primary systems of timber/pulp and crop production are also in continuous interaction with the ecological, economic and social factors. These chains of interactions exacerbate the complexity of forest and crop residues-based bioenergy production as secondary systems. Implementation of alterations in operational processes and the sectoral policies that are interlinked with the bioenergy production value chain can result in undesirable performance of the bioenergy system over time when the approach to bioenergy production is not integrated in the policies. Furthermore, technological and policy innovations in the primary systems may have direct and indirect implications on availability of the residues, reliability of the bioenergy systems and security of supply of the bioenergy products to end users. Therefore, assessing and modelling sustainable production of residues-based bioenergy systems is complex and requires an approach with inherent capabilities of analysing complex interconnected and interacting structures, and demonstrating the consequences of these interactions over a long time horizon. In this way, state limiting processes in the supply chain of the residues can be identified and technological, processes and policy innovations that can promote resilience of the residues value chain can be developed so that residues-based bioenergy production can contribute to meeting the local and macro energy needs in a sustainable way.

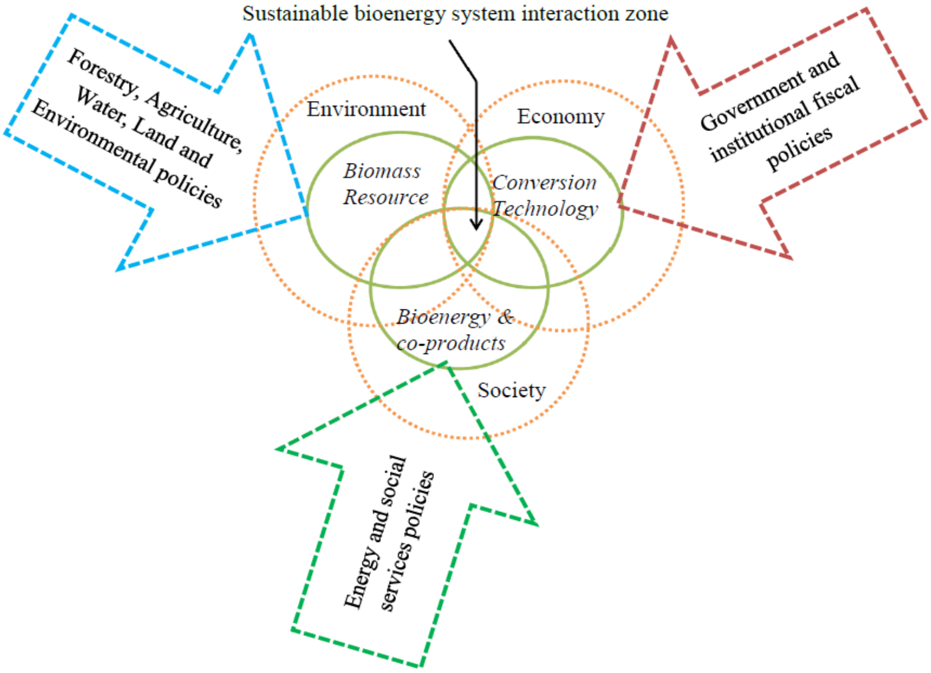

Figure 1.1: Complex links of the subsystems (components) of a bioenergy system with environmental, economic and social factors and between the bioenergy system and sectoral policies.

1.3 Approaches to assessing sustainable production of bioenergy

Many approaches to assessing sustainability of bioenergy production have been suggested by various scholars. A detailed review of these approaches is presented in the literature review in Chapter 2. For instance, Buchholz et al., (2009); Wang et al., (2009); Karagiannidis and Perkoulidis, (2009); Elghali et al, (2007); Løken, (2007); Poheker et al., (2004); Afgan et al., (2002) suggest a multi criteria decision analysis (MCDA) technique. Oliveira et al., (2008) have applied the sustainability analysis and data enveloping methods. Karpenstein-Machan, (2013) has suggested integrative cultivation of farm land. However, these approaches analyse single component of bioenergy production. They are static and incapable of analysing and demonstrating the dynamic behaviour inherent in complex system involving many interconnected and interacting components. In order to model the dynamic complexity of forest and rice residues-based bioenergy production, the systems approach, based on systems thinking and system dynamics methodology, which has inherent capabilities to map the effects of the interrelationships of the structures in a system and demonstrate the pattern of system behaviour over time (Forrester, 1968), has been used in this study. The approach has been applied on two residues-based bioresources supply chains: a perennial non-food supply chain of primary forest residues from Viphya forest plantations in Nkhata Bay and Mzimba districts and an annually produced rice residues (food related) value chain in rice farms in Karonga district in Malawi. The theory of system approach is provided in section 2.4 of Chapter 2.

1.4 Motivation for systems approach modelling of residues-based bioenergy production

The motivation for this study was based on the following:

(i) The lack of inclusion of the dynamics that are at play in residues-based bioenergy systems in the existing methods for assessing, estimating and reporting availability and bioenergy potential of forest and rice residues for bioenergy production. As presented in section 1.2, the interconnectedness of the components of bioenergy production from forest and crop residues, and the interactions between sets of the components and structures, from forest management and rice farming systems to bioenergy generation and allocation to end use processes, are complex. Additionally, assessment of the chain of components, technologies, processes interlinked in production, mobilization, supply and conversion of the residues to modern forms of energy, economic, social, and environmental factors, policy and management practices along the value chain (Musango & Brent, 2011), requires a modelling approach with inherent capability of capturing the causalities of the interactions.

As pointed out by Ford & Sterman, (1998), the lack of understanding of the dynamic relationships of the components of a complex system, with nonlinear feedback structures, is the influencing factor of poor management and performance of systems. Decision makers at technical, investment and policy levels of bioenergy systems development need strategic information to support technological, process and policy innovations that can promote resilience of the residues supply chains against contextual changes along the bioenergy production value chain. In order to develop a sustainable primary forest and rice residues-based bioenergy system, the feedback processes, nonlinearities and time delays and their effects in the system that may constrain availability, reliability and security of supply of bioenergy to end use processes, need to be understood.

(ii) Innovations in conversion routes and technologies of bioresources have enabled efficient conversion of primary forest and rice residues into many forms of bioenergy and bio-products (IPCC, 2007; IEA, 2012). However, these innovations alone may not be adequate to promote sustainability of residues-based bioenergy systems and bioenergy production and supply to end users. The conversion routes and technologies of the bioresources to bioenergy and bio-products are not autonomous. The characteristics of the residues, choice of the conversion routes and technologies, and the forms of energy needed by the end users are interrelated (McKendry, 2002). In addition, the choice of scale of the biomass conversion plant is related to feedstock availability, economic viability of the bioenergy project and the energy demand (McKendry, 2002; IEA, 2012). Furthermore, the conversion routes and technologies are in continuous interactions with economic, environmental and social factors as presented in Figure 1.1. Changes in social, institutional, economic and environmental policies and practices in the value chain, from residues production to bioenergy allocation to end users, have the potential to exacerbate sustainability challenges in the bioenergy systems.

(iii) The intertwinement of processes and activities in bioenergy production from primary forest and rice residues in the energy, forestry, agriculture, environmental, water and other national and institutional social and fiscal policies exacerbates the complexity of the residues-based bioenergy systems. These policies involve many stakeholders with varied backgrounds, experiences and conflicting interests (Buchholz et al, 2009). The broad scope and interconnectedness of the processes and the conflicting interests of the stakeholders have the potential to influence dynamic behaviour in the residues-based bioenergy systems.

(iv) Primary forest and rice residues-based bioenergy systems encompass broad scope of processes utilising bioresources that are produced and sourced from the environment. Previous studies have reported on the environmental impacts of exploiting the residues for bioenergy production that include increase in CO_2 emissions, reduction in soil microbial carbon, decrease in humus and site productivity in plantations (Repo et al., 2015; 2011). However, the dynamics in the stocks of the principal components (timber and rice), the residues, and bioenergy production and supply to end use processes over time, as a consequence of exploitation of the residues, have not adequately been mapped, evaluated and demonstrated and need to be understood.

(v)Interactions between the components of the bioenergy system, the dependency of availability of the residues on timber and crop production (Bolkesjø et al., 2006) and the interaction of sectoral policies, regulations and practices may generate stress in the environment and in the value chains of the residues, bioenergy production and energy supply to end users. Thus, bioenergy production from primary forest and rice residues needs to be produced in a way that it does not compromise the needs of the sectors in which it is intertwined while meeting the energy needs of the end users. The emphasis on identifying and investigating effects of the feedback structures and delays in a system makes system approach a valuable and appropriate method for assessing sustainable production of bioenergy from forest and rice residues. The application of systems approach to modelling sustainability of residues-based bioenergy system is aimed at achieving simultaneous long term stability in production of the principle components generating the residues and bioenergy without compromising environmental and social benefits that can be accrued from the systems.

(vi) The potential of bioenergy from forest and rice residues to contribute towards meeting the local and macro energy needs in a sustainable way can be realised when enablers and disenablers to long term availability of these bioresources are understood. In the context of this study, enablers to bioenergy development are those factors that can promote development and implementation of sustainable bioenergy production systems while disenablers are the state limiting factors to development and implementation of bioenergy. The systems approach has been used in a case study of primary forest and rice residues value chains in Malawi. The approach has been used to demonstrate the causal-effects relationships of interactions of the systems components, shown in Figure 1.1, in the supply chains of the residues. The purpose was to gain insights of the potential enablers and disenablers to steady flow of residues for bioenergy production. Application of the systems approach in this study has facilitated development of process and policy innovations needed to promote stability in timber and rice production, which in turn can promote steady flow of the residues for bioenergy production. The criteria for choosing the primary forest and rice residues value chains is presented in Chapter 2, sections 2.4 and 2.5.

1.5 Background of study area and problem statement

1.5.1 Primary forest and rice residues value chains in Malawi

Primary forest residues and rice straws and husks are locally available in rural areas in Malawi where forest plantations and rice farms are located (Zalengera et al., 2014). Zalengera et al., (2014) have reported annual production of 61875 cubic metres of forest residues and 7 million tonnes of both crop residues and animal dung in Malawi. However, the dynamics in the supply chains of the residues have not been assessed to provide insights of the enablers and disenablers to long term availability of these residues within the context of prevailing production and harvesting systems.

Inadequate assessment and mapping of the residues value chains can limit innovations to promote resilience of the residues supply chains to bioenergy production. Energy requirements for process operations in the residues supply chains that can support virtuous integration of timber and bioenergy production in forest plantations, and rice and bioenergy production in rice farms need to be identified. Understanding the energy needs of state limiting processes to production of the principle components in the value chains can promote targeted supply of bioenergy to the processes thereby promoting the virtuous integration of bioenergy and timber and rice production.Additionally, the supply of bioenergy and bio-products to end users, which are not in end users' interests and do not meet critical energy needs that can support resilience of the bioenergy value chain, can have significant implications on stakeholders' participation in bioenergy production and utilisation.

This study focused on bioresource mapping and value chain analysis of primary forest residues from Viphya forest plantations of *Pinus patula* and *Pinus kesiya* located in Mzimba and Nkhata Bay districts (Fig. 1.2a) and rice straws and husks from rice farms in Karonga district (Fig. 1.2b) in Malawi. Particular attention was paid to deployment strategy and the scale of the bioresource conversion plant to feedstock supply in sizing of the bioenergy systems for rural areas with dispersed feedstock supply. Consequently, mapping of primary forest and rice residues and analysis of their supply chains formed part of the assessment and sizing of the bioresources processing operations.

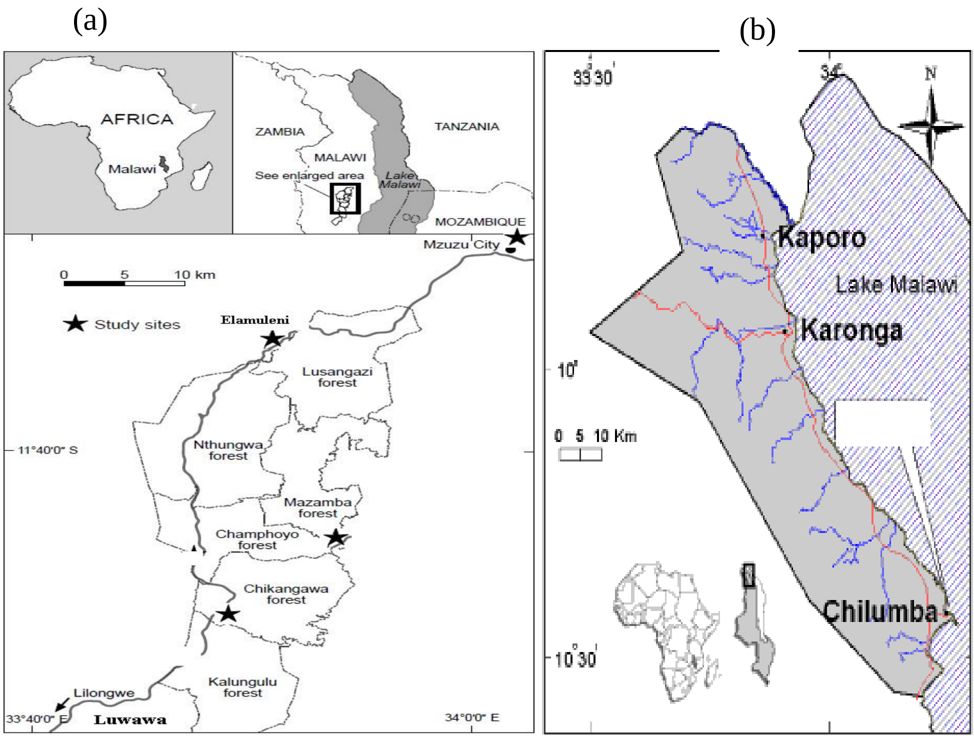

Figure 1.2: Study areas (a): Map of Viphya forest plantations showing study sites: Mazamba area, Chikangawa, Elamuleni and Mzuzu City. Adopted from Ngulube et al., 2014 with minor modification (used with permission from E. Ngulube, Forestry Department, Mzuzu University); (b): Map of Karonga district showing the sources of water used for rice production flowing from Nyika highlands through Karonga district to Lake Malawi. Used with permission from Mia Crampin, Karonga Prevention Study/London School of Hygiene & Tropical Medicine. Source: http://www.lshtm.ac.uk/eph/ide/research/kps/district/

The residues resource mapping was conducted in order to identify the segments in the bioenergy production value chain that are state limiting to scale of operations and those that can have enhancing effect with small modifications in order to further improve on the effects of economies of scale and the dynamic behaviour of the bioenergy system. The value chain analysis enabled identification of feedback structures at play in the primary forest and rice residues-based bioenergy production emanating from the internally generated system structures in the value chains of the two feedstock streams, from production of the residues to energy allocation to end use processes.

Furthermore, process and policy innovations in primary forest and rice-residues based bioenergy systems can be promoted when the enablers and disenablers in the supply chain of the residues are understood, which in turn can improve the production and postharvest management systems of the residues beyond forest plantations and the rice farms. The dispersed nature of the rice residues is a limiting factor to the scale of the conversion technologies that can be installed for bioenergy production and on availability and reliability of the bioenergy systems within the constraint of distance from the forest plantations and rice farms and mills where the residues are produced. Therefore, bioenergy supply options to processes that are state limiting operations to implementation of bioenergy in rice farms need to be investigated in order to promote sustainable production of bioenergy from the residues.

1.5.2 Problem statement and research questions

1.5.2.1 Problem Statement

The review of the existing approaches for assessing sustainability of forest and rice residues-based bioenergy production and the value chain analysis of the residues presented in sections 1.3 and 1.6 have revealed that:

(i) Methods for assessing availability of primary forest and rice residues for bioenergy production have not adequately addressed potential dynamics in the residues-based bioenergy production to identify enablers that can promote resilience of the systems against contextual changes in process, technology and policy in primary systems that generate the residues. The methods are static, lack the capability to demonstrate the type and level of influence between interacting variables, and do not adequately show the potential dynamic behaviour over time of the bioenergy systems.

(ii) Energy and economic value of bioresources from primary forestry and rice residues in Malawi have not been realised, the value chains of these resources, as feedstock for bioenergy production, have not been adequately assessed and the residues are being underutilised.

(iii) The lack of strategic information such as the size and long term availability of the supply chain of primary forest and rice residues limit utilisation of primary forest and rice residues for bioenergy production. In addition, decision makers at investment and policy formulation levels lack information on viable conversion routes and technologies, scale of bioenergy production plants and forms of energy from primary forest and rice residues that can have the most impact in the energy mix in Malawi.

1.5.2.2 Research Questions

This study examined the following key question:

(i) What are the state limiting processes and potential sources of dynamics in primary forest and rice residues value chains?

(ii) What are the key feedback structures at play and their impacts in the primary forest and rice residues-based bioenergy systems?

(iii) What technological, process and policy innovations can promote resilience of the sources of feedstock, bioenergy production and supply in the primary forest and rice residues-based bioenergy systems?

1.6 Research objectives

1.6.1 Underlying objective

The main objective of this study was to develop a systems approach model for sustainable production of bioenergy from primary forest and rice residues.

1.6.2 Specific objectives

The specific objectives of this research were:

(i) To assess availability, bioenergy potential and viable conversion routes of primary forest residues from Viphya forest plantations and rice straws and husks from rice farms in Karonga district in Malawi for rural community energy supply.

(ii) To develop, populate and test systems approach model for sustainable production of bioenergy from primary forest residues and rice straws and husk in decentralised modular systems in Malawi.

(iii) To develop a bioenergy production framework for sustainability of primary forest and rice residues-based bioenergy systems.

The desired goal in the systems approach model for sustainable production of residues-based bioenergy was to attain a stable flow of the residues to a conversion plant over time that can promote stability in power (energy) generation, system availability when energy is needed, reliability of the system to supply the design output energy needed by the end use processes and security of energy supply to end users.

1.7 Research approach

This research was multidisciplinary in nature and involved applying engineering and social sciences skills and quantitative and qualitative data collection. In addition, the systems approach modelling methodology used in this study involves interactions with stakeholders that are directly and indirectly involved in the systems to collect the relevant data for populating the model. The activities followed to achieve the study objectives are presented in the flow diagram in Figure 1.3. The research approach covered the following:

- A review of the literature on bioenergy production and approaches to assessment of sustainability of bioenergy systems to identify existing gaps.
- Identification of the dynamic systems approach and its applicability to assessing sustainable production of bioenergy from various feedstocks.
- Literature review on system dynamics modelling methodology and mastering Vensin and Structural Thinking, Experimental Learning Laboratory with Animation (STELLA) Architect system dynamics modelling software.
- Identification of key stakeholders in the residues value chains and analysis of stakeholders' influence, interest and potential involvement in bioenergy production from the residues in a field survey conducted in Malawi from January to April 2015. The aim of the survey was to assess the production processes and quantities of the residues, and the energy needs that can be supplied with bioenergy and can have the most impact on promoting sustainable production of bioenergy from the residues in Malawi.

- Onsite assessment of production and postharvest management of primary forest and rice residues.
- Developing the systems approach model for sustainable production of bioenergy (SAS-Biopro model). The objectives of this step were to:
  - (i) identify the state (stock levels) of the primary forest and rice residues,
  - (ii) to identify the causal-effects relationships of interactions between sets of processes in the residues supply chains on the state of the residues,
  - (iii) to identify leverage points where technical or policy innovations can result in stability of the residues production and supply for bioenergy production, and
  - (iv) to develop strategies for deployment of the residues-based bioenergy systems that can promote sustainability of bioenergy and timber production in the primary forest residues value chain and bioenergy and rice production in the rice residues value chain.

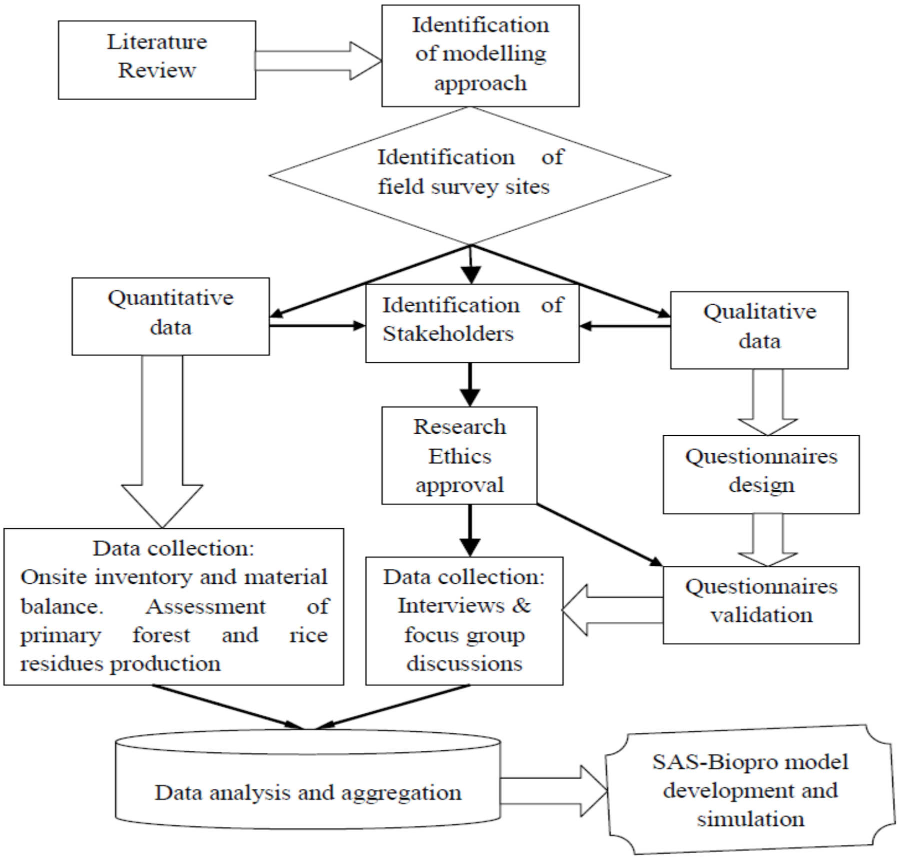

Figure 1.3: Flow diagram for the research conceptualisation and implementation for the development of the systems approach model for sustainable production of bioenergy (SAS-Biopro) model.

1.8 Research novelty

A systems approach model for sustainable production of bioenergy (SAS-Biopro model) was developed in this study using system dynamics modelling techniques for modelling complex nonlinear multidisciplinary systems. The model provides a planning tool for assessing resilience (availability and stability) of residues-based bioresources supply chains over time for bioenergy production. The technical information generated from the model can promote process oriented integration of residues-based bioenergy systems and the systems that generated the residues. Specifically, this research contributes a paradigm shift from fragmented approach to deployment and operation of the residues-based bioenergy systems and the systems that generate the residues to whole systems and synergetic integration of the systems. The approach can promote synchronised scale of alterations in operational processes and policies in the primary systems and the scale of operation of the bioenergy conversion plant. Holistic integration of the systems can promote resilience of the residues supply chains against changes at any point in the residues production value chain. The SAS-Biopro model shows the following attributes:

(1) The effects of interactions between operational processes in primary systems (forest management and rice farm management) on the secondary systems (forest and rice residues-based bioenergy production), which may cause variations in bioenergy production. It gives insights of the technological, process and policy innovations needed to promote resilience of the systems over time, which is a critical indicator that is not captured by other modelling approaches. Although the three sub systems of bioenergy system (feedstock supply chain, conversion process and technology and energy allocation to end users) are targeted, the SAS-Biopro model gives insights of the influence of the social factors originating from stakeholders' power and interest in the primary systems on the dynamic behaviour of the residues-based bioenergy systems. Therefore, the development of synergetic integration framework, although approached from the technology and process point of view, is flexible to respond to policy and societal changes in the value chain of bioenergy production.

Points of high leverage in forest plantations management and harvesting systems, and sizing bioenergy plant scale where small changes in processes can promote steady flow of the residues for bioenergy production over time. For instance, from the simulation results of the SAS-Biopro model, this study has established that sustainability of primary forest residues-based bioenergy systems can be promoted by:

(i) setting an annual harvesting threshold of mature stand evaluated using maturity time of predominant tree species and the total area of the forest plantations;

(ii) matching the scale of operation of the conversion plant with the amount of residues produced from the annual harvesting threshold of mature stand,

(iii) synchronising harvesting and replanting of the harvested sites; and

(iv) minimising replanted trees mortality fraction to <0.1 in the forest plantations.

The SAS-Biopro model demonstrates that stability of an optimum amount of forest residues for bioenergy production can be promoted by harmonising alterations in management and harvesting systems of forest plantations. In addition sizing the scale of operation of the bioenergy conversion plant based on optimum amount of annually generated residues can promote system availability. Furthermore, the model shows multiple benefits to the environment. The cascaded growth of the forest stand into immature, maturing and mature stand over the maturity period of the tree species replanted in the harvested sites, promotes carbon sequestration potential of the plantations and ecosystem balance for plants, wildlife and other natural resources that survive on the forest plantations. Therefore, whole systems integration of bioenergy and timber production in forest plantations is an innovative approach that can promote identification of enablers and disablers that together, rather than in isolation are the backbone for informed bioenergy innovations and technology transfer in the forest residues value chains in Malawi. These factors might otherwise not be identifiable with single component analysis approaches which have been applied in bioenergy systems development.

(2) The synergetic integration of bioenergy and rice production in rice farms is a novel approach to deployment of rice residues-based bioenergy systems developed in this study. The SAS-Biopro model shows that the approach can promote resilience of the rice residues supply chain and sustainable production of bioenergy and rice in the rice farms without alienating land from production of other crops. The approach promotes multiple cropping of rice, which can have multiple benefits to the rice farmers such as access to electricity and financial gains from sales of surplus rice

from dry planting. In the model, the increase in rice production as a result of multiple cropping increases annual rice residues production that increases bioenergy production. Bioenergy supplied to irrigation water pumping increases rice production, which can promote food security and financial benefits from sales of the excess rice.

(3) Systems approach modelling has been used in the energy sector in developing models for biodiesel policy design, analysis and technologies sustainability assessment (Espinoza et al., 2017; Barisa et al., 2015; Musango, 2012), energy technologies for sustainability assessment (Musango and Brent, 2011), bioenergy systems sustainability assessment (Stafford and Brent, 2011), energy policy planning (Naill, 1992). However, the approach has been used for the first time in this study, in combination with the conventional methods of residues to product ratio, onsite forest residues inventory, bioenergy potential and macro-economic viability evaluation, and a layered five-step sustainability analysis, to assess sustainability of residues-based bioenergy production.

1.9 Contribution to knowledge

This research contributes to process innovation of systems integration of residues-based bioenergy production and the systems that generate the residues used for feedstock for bioenergy production in order to promote resilience of the source of the residues and the supply chain against contextual changes in the value chain. Using the systems approach modelling methodology to map the residues supply chains, this study has shown that technological, process and policy changes in the systems that generate the residues can be enablers or disenablers to long term availability of the residues. In addition, the approach demonstrates that availability and reliability of the bioenergy system, to supply the energy products needed by energy end users can be promoted by systems approach modelling of the systems as a unit system. Process and policy integration can support synchronised scale of adjustments in the primary and secondary systems that can simultaneously promote sustainability of bioenergy and the principal components in the primary systems.

Although the systems approach modelling techniques have been used for assessing sustainability of purposely grown biodiesel crops for biodiesel production in Eastern

Cape in South Africa (Musango, 2012), this study has tested the techniques for the first time in assessing sustainability of residues-based bioenergy systems. The objective was to promote holistic integration of bioenergy systems utilising residues-based bioresources for feedstock and the primary systems that generate the residues for sustainable production of bioenergy and the principal components in the primary systems, simultaneously.

1.10 Dissertation layout

This dissertation is structured based on journal articles published and manuscripts submitted for publication or in final revised format for submission. The sequential order of the layout of the articles in the dissertation is based on the sequential order of addressing the research objectives on each of the two feedstocks: (i) primary forest residues and (ii) rice residues, which have been investigated in this study. The chapters are organised as presented in Figure 1.4.

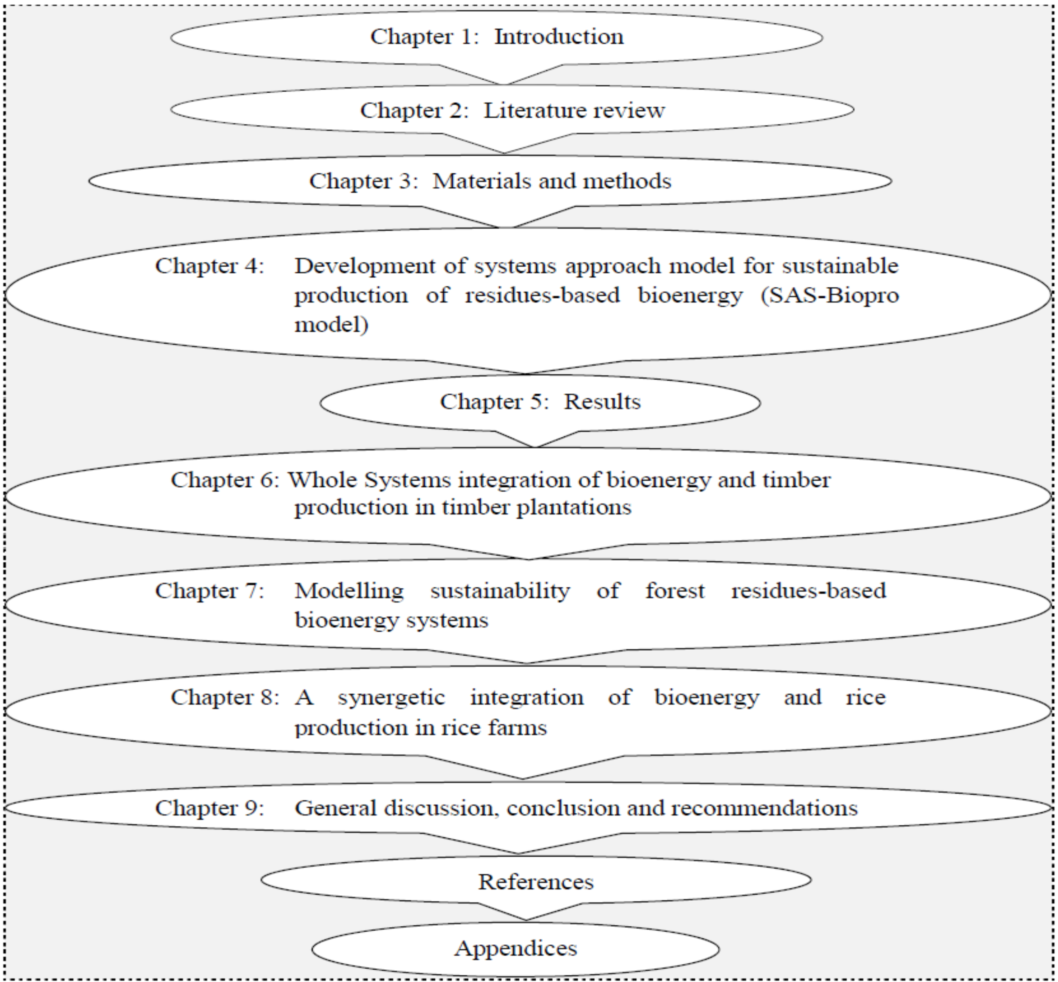

Figure 1.4: Layout of chapters in the dissertation

Chapter 2: Literature Review

2.1 Introduction

This chapter provides a review on approaches used for assessing availability, bioenergy potential and sustainability of primary forest and rice residues. The chapter also provides review of literature on forest management and rice farming systems, as sources of residues for bioenergy production. In addition, conversion routes and forms of energy and bioenergy products were reviewed. The reviewed literature show that the methods used in assessing availability and sustainability of bioenergy production from forest and rice residues, have not adequately addressed the causalities of the interconnectedness and interactions between the primary systems generating the residues and the bioenergy systems, as secondary systems utilising the residues for energy generation.

The chapter underscores the appropriateness of using the systems approach modelling techniques, based on systems thinking and system dynamics modelling methodology, to assessing the value chains of bioenergy production from primary forest and rice residues to promote resilience of the residues (feedstock) supply chains, and availability, reliability and security of supply of bioenergy to end use processes.

2.2 Assessment of sustainability of bioenergy systems

Many approaches to assessing sustainability of bioenergy systems have been suggested by scholars in biomass and bioenergy production. Buchholz et al., (2009); Wang et al., (2009); Karagiannidis and Perkoulidis, (2009); Elghali et al, (2007); Løken, (2007); Poheker et al., (2004); Afgan et al., (2002) suggest multi criteria decision analysis (MCDA) technique for assessing sustainability of bioenergy systems. MCDA is based on participatory approach for selecting a viable biomass conversion technology option and aims at enhancing social acceptance of the energy supply system (Buchholz et al., 2009). The conversion technology is selected based on consensus of the views of the stakeholders, which is arrived at by scoring the technology options against a set of sustainability criteria. The technology with the highest score is selected as the viable option. In addition, MCDA is viewed as a useful tool for generating information on stakeholders' opinion through social engagement that enables decision makers and stakeholders to choose the best alternative bioenergy conversion technology from among an array of technologies. Buchholz et al., (2007, 2009); Afgan et al., (2002), have observed that MCDA is an evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty and conflicting objectives of stakeholders. However, MCDA techniques are linear, static and lack the capability of analysing variations over time (dynamic performance) in process and resource flows inherent in complex nonlinear systems such as residues-based bioenergy systems. MCDA techniques cannot adequately assess nonlinearities and generate visual information that can give insights of high leverage points for technological, process and policy innovations in the residues-based bioenergy production value chain.

In addition, MCDA techniques are prone to subjective scores based on opinion, interest, training (educational) background and expertise of influential stakeholders involved in assessing sustainability of bioenergy systems. For instance, Buchholz et al., (2009) evaluated sustainability criteria of bioenergy systems using multi criteria decision analysis in Uganda using a sample of stakeholders drawn mostly from a population of biomass industry experts. This category of stakeholders, consistently rated environmental indicators (greenhouse gas and energy balance) as most important indicators that are practical, reliable and relevant for assessing sustainability of bioenergy systems. On the other hand, social and economic indicators were rated lowly. Therefore, decision support frameworks (DSF) in residues-based bioenergy production, developed based on MCDA techniques, may be biased and may not adequately capture the dynamic performance (the causal-effects relationships) of the bioenergy system emanating from the interconnectedness of the environmental, economic and social components of the system.

The potential of subjective scoring of the technologies in MCDA can promote development and implementation of processes and policies that can result in dynamic performance of the forest and rice residues-based bioenergy value chains. Furthermore, MCDA methodology is an open loop process that lacks the capability of analysing the effect of subjective choice of the bioenergy technology on the performance of the whole bioenergy system over time.

Other approaches such as assessment of availability of feedstock production and supply by estimating surplus land, which can be committed to cultivation of biomass through improved agricultural practices, have been used to estimate future availability of biomass feedstocks. Junfeng and Runqing, (2003) have used this approach to assess sustainable biomass production in China. Lauri et al., (2014) estimated availability of woody biomass up to the year 2050, from the perspective of energy wood supply curves for large scale biomass conversion plants at various hypothetical energy wood prices using Global Biosphere Management Model (GLOBIOM). GLOBIOM is a model used in agriculture and forest sectors that estimates the area that can be utilised for biomass (feedstock) production and the bioenergy potential of the biomass. However, these approaches evaluate a single component of feedstock supply chain without considering the interconnectedness of the components of the bioenergy production systems. In addition, the effects of interactions between the feedstock supply chain and the other components of the bioenergy system are not demonstrated using these approaches to assess sustainability of the bioenergy systems.

Oliveira et al., (2008) have applied the sustainability analysis and data enveloping methods to assess sustainability of wastes as feedstock for biodiesel production in Brazil based on selected economic, technological and environmental indicators. The sustainability analysis and data enveloping methods are based on impact of input materials for bioenergy production on greenhouse gas emissions, job creation, operation and maintenance of the bioenergy technologies and investment costs as key sustainability indicators. Their results show positive net benefits and competitiveness of biodiesel production from wastes when compared to purposely grown energy crops. However, the effects of variations in production and availability of the bio wastes for biodiesel production on long term availability of biodiesel production and supply to end users, and the impact of biodiesel production on the bio wastes production and supply chain have not been analysed.

Karpenstein-Machan, (2013) has suggested integrative cultivation of farm land to promote sustainable production of bioenergy. The concept involves a combination of different landscape utilisation options on farm land to produce food, fodder and energy, as well as support wildlife. The goal of integrative cultivation is to promote utilisation of farm land by harmonizing production and protection of landscape in which agricultural production and landscape management are not mutually exclusive thereby maximizing available landscape for both food and bioenergy. Key sustainability indicators in integrative cultivation include: land use, food security, ecosystem management and biodiversity among others. However, the methodology focuses on one component of feedstock production, and it is static and lacks the capability of analysing and demonstrating the long term effects of the approach on the feedstock production and supply chain.

Integrated assessment modelling approach (IAM) for value assessment has been used to track and forecast a range of values across environmental, social, economic and technical spheres. Millward-Hopkins et al., (2018) have argued that multi dimensional assessments can be better performed by integrating the calculation methods of one-dimensional models rather than their inputs. IAM methods are useful for modelling complex systems to capture material transformation, creation and destruction in the technical, economic, environmental and social spheres of the system under study. IAM methods require extensive input data on material flows captured over time from the system being modeled. The lack of longitudinal data on material flows in the primary systems (the forest plantations and rice farming management systems) in the case study areas over the 14 and 10-year periods respectively, limited the application of IAM methods in this study. IAM methods can be considered for assessment of residues-based bioenergy systems in locations/regions with satisfactory data recording and management systems. The methods can be considered for further studies in Viphya forest plantations and rice farms in Karonga if data recording and management can be improved.

Life cycle assessment (LCA) methods have been used for the assessment of environmental impacts linked to bioenergy projects (Forsberg, 2000; Cherubini et al., 2009; Cherubini & Strømman, 2011). The LCA methods allow identification and evaluation of materials, energy and carbon flows (mass and energy balance) attenuated by the bioenergy system (Cherubini et al., 2009; Cherubini & Strømman, 2011). In addition, the LCA methods provide opportunity to identify areas for improvement on the environment in the locality and within the boundary of the bioenergy system (Cherubini et al., 2009; Cherubini & Strømman, 2011). The scope of the LCA, the criteria and indicators used vary based on the functional unit (component) of the bioenergy system and the type and source of the bioresource feedstock under consideration (Cherubini & Strømman, 2011), which result in variations of the results.

LCA is a strong environmental tool in sustainability analysis and generates valuable information for decision-making on environmental impacts of the bioenergy project. The methodology can be used to analyse potential environmental impacts of technological, process and policy innovations that can be identified and developed in systems approach modelling.

It can be observed that the methods for assessing availability, bioenergy potential and sustainability of bioenergy systems reviewed in this study generate useful information for decision making on the components of bioenergy systems that are assessed. The methods satisfy the objectives that the methodologies were developed for, the decision level and decision variables addressed in the assessment of the systems. In addition, the methods satisfy the mathematical methodology used to develop the methods and vary in scope of parameters used. As pointed out by Musango (2012), sustainability of bioenergy production is complex, and with nonlinear feedback structures owing to its dependency on anthropogenic activities. In addition, the interconnectedness of the components of the bioenergy system (Fig. 1.1) with the technical, ecological, economic and social factors (Musango and Brent, 2011; Buchholz et al., 2007; 2009), and the interactions between the whole system with the policies of the sectors that generate the residues, exacerbate sustainability challenges of residues-based bioenergy production. The anthropogenic activities and practices emanating from the policy statements may promote state limiting processes along the value chains of feedstock mobilisation, conversion and energy allocation to end use processes. Knowledge of the processes, technologies, and local policies of the sectors in which bioenergy production processes are intertwined and institutional capacity to sustain the system is critical to development of sustainable bioenergy systems.

Furthermore, Costello & Finnell, (1998); McCormick and Kaberger, (2007); Zalengera et al., (2014) have pointed out the role of stakeholders along the bioenergy production value chain, local political, economic, social acceptance, technical-know how, legal and environmental conditions, institutional capacity and policy implications of the bioenergy development projects to have significant influence on implementation of bioenergy systems. These studies have shown that knowledge of key stakeholders' influence, interest and motivation to participate in the bioenergy production value chain is critical for the development of sustainable bioenergy systems. The impacts that reliability of the bioenergy system and security of energy supply to end use processes can have on stakeholders' interest and motivation over time have to be understood for development of bioenergy systems that are socially acceptable by investors in bioenergy systems, feedstock mobilisers, energy end users and policy makers. It is also important that the stakeholders' preference of the forms of energy needed to meet the local energy needs and how the bioenergy generated from the residues can be allocated to end use processes that can have the most impact are understood in the context of the local social, ecological, economic and technological constraints.

2.3 Value chain analysis of primary forest and rice residues

Bioenergy production from residues and bio-waste materials has attracted the interest of researchers to assess availability, bioenergy potential and viable conversion routes and technologies of these bioresources (Iye & Bilsborrow, 2013; Jiang et al., 2012; Scarlat et al., 2011; Weiland, 2010; Khanal et al., 2008; Rossillo-Calle et al., 2007; Lewandowisk & Faaij, 2006; Bridgwater et al 2002; McKendry, 2002; Demirbaş, 2001). The surge in bioenergy production driven by innovations in converting the residues to different forms of energy and bio products (Bridgwater et al 2002; McKendry, 2002) provides the opportunity of developing bio-wastes and residues-based bioenergy systems that can contribute to renewable and clean energy supply portfolio. Bioenergy, systems based on residues and bio wastes, can contribute to meeting the local energy needs in areas where the residues are produced.

Yilmaz & Selim, (2013); IPCC, (2011); McKendry, (2002) have observed that the characteristics and quantity of the available bioresources in an area, the form(s) of energy needed by the end users, economic viability and maturity of the conversion route and technologies in relation to the energy needs, influence the selection of appropriate conversion routes and technologies of the bioresources. Therefore, onsite value chain analysis of primary forest and rice residues is essential to gain insights of the type, characteristics and quantities of the residues, energy needs of rural communities in the areas that generate the residues for selection of appropriate and economically viable conversion route and technology.

Primary forest and rice residues have been widely assessed as potential feedstocks for bioenergy production (Zalengera et al., 2014; Guest et al., 2013; Iye & Bilsborrow, 2013; Jiang et al., 2012; Binod et al., 2010; Yamamoto, 2001). These residues are locally produced in regions with forest resources and rice farming activities, respectively (Akhtari et al., 2014; Ramamurthi et al., 2014; Guest et al., 2013; Levin et al., 2007; Binod et al., 2010). As observed by Iye & Bilsborrow, (2013 Jiang et al., (2012); Scarlat et al., (2011), accurate assessment of availability of forest and crop residues at local level, is a precursor technical aspect to the development of viable bioenergy systems to utilise the residues supply chains.

Various methods have been used to assess availability and bioenergy potential of forest and rice residues. Residues to product ratios (RPR), area of land cultivated with agricultural crops and geographical information systems (GIS) methods, in combination with heating values of the residues, have been used for assessing availability, bioenergy potential and sustainability of forest and rice residues for bioenergy production (Shane et al., 2016; Kizha & Han, 2015; Monforti et al., 2015; Parzei et al., 2014; Viana et al., 2010; Fernandes & Costa, 2010; Noon & Daly, 1996). These methods have generated valuable information on the amount and bioenergy potential of the residues which can be used for planning for development of bioenergy systems. However, RPR and GIS methods are static and insufficient of demonstrating the dynamics in production of the residues arising from management policies, anthropogenic activities and practices in harvesting of forest plantations and rice farms, and post harvest management of the residues over time. In addition, the lack of a standardised approach to assessing long term availability of primary forest and crop residues, lack of tracking mechanism of the variations in stocks of mature stand in forest plantations for timber and residues production, and predicting the long term effect of the competing uses of the residues along the supply chains, have the potential to exacerbate sustainability challenges of primary forest and rice residues-based bioenergy systems.

The variability in RPR values in literature and the influence of logging and sawmilling technologies, harvesting systems and well-being and age of the forest stands on the amount of residues that can be generated per unit of forest stand (Owusu, 2011; van Dam & Faaij, 2007; Lewandowski et al., 2006; Dionco-Adetayo, 2001; Okuneye et al., 1986), present a critical challenge to adopt and apply the RPR values evaluated in forest plantations from other regions and economies for mapping forest residues for sustainable production of bioenergy. For instance, Okuneye et al., (1986) have reported RPR values in forestry that range between 0.1 and 0.5 from a wide spectrum of the wood industry processes, from logging operations in forests to wood processing, at wood factories and processing plants in Nigeria in which 50% of the residues were generated from logging operations. In contrast, Dionco-Adetayo, (2001) reviewed utilisation of wood wastes in the same region and found that logging residues consisting of barks (50%), rejected round logs (3.75%), tops and branches (33.75%), stumps (10%), and butt trimmings (2.5%), constituted for about 80% of the harvested mature stand.

Furthermore, a study by Owusu et al., (2011) in Ghana indicates residues generation fraction (rgf) values ranging between 0.17 and 0.25 for Wood-Miser mills. However, logging residues usually left on the harvest site in the forest plantations were not included in the study. van Dam & Faaij, (2007) estimated the contribution of forest residues to the biomass potential in Central and Eastern Europe from the total annual demand for round wood and the ratio of the volume of all trees living or dead felled and removed from the forest per hectare. However, unpredictability of dead wood in plantations presents the challenge to determine the ratio of residues that can be realised from natural mortality of trees per unit of forest stand. Lewandowski et al., (2006) calculated the amount of forest residues for energy production in the Czech Republic from the amount of harvested round wood and have reported the wood to residues ratio ranging between 0.1 and 0.15, which were used in the assessment of the potential biomass that can be available for energy generation. Lim et al., (2012); Gadde et al., (2009) have reported residues to product ratio of rice straws ranging between 0.41 and 3.96 of every kilogram of paddy harvested. Scarlat et al., (2010) reviewed twenty two studies on RPR values and have reported residues to product ratio of rice residues ranging between 0.28 and 2.3. Matsumura et al., (2005); Kadam et al., (2000) have reported RPR values for rice residues of 1.43 and 1.35 respectively. Thus, RPR values reported in literature vary based on the objective of the study which determined the characteristics of the residues that were included or excluded in the assessment.

The variations observed in literature on RPR values used for assessing availability of primary forest and rice residues and the lack of standard amount and characteristics of the residues that should be left in the harvested areas necessitate onsite assessment of management and harvesting systems applied in the forest plantations and the rice farms to validate the RPR values. Interactions of micro level structure in planting and replanting schedules and harvesting processes in forest plantations need to be understood. The quantities, predominant characteristics and competing uses of the residues (Monforti et al., 2015; Scarlat et al., 2010) and the effects of the competing uses on long term availability of the residues supply chains need to be assessed in order to promote accurate evaluation of availability, bioenergy potential and socio-economic and environmental impacts of the residues-based bioenergy value chain at local level.

Geographical Information Systems (GIS) methods are useful for mapping locations of the bioresources, quantities of the bioresources at each location and potential sites for installation of bioenergy conversion plants. Viana et al., (2010); Voivontas et al., (2001) used the GIS method to develop a decision support system (DSS) to provide the tools for identifying the geographical distribution of the economically exploitable biomass potential of agricultural residues. Beccali et al., (2009) assessed the technical and economic potential of biomass exploitation for energy production in Sicily using the GIS-based methodology that supports defining potential areas for gathering the residues. However, the GIS platform requires input statistical data on type, quantities and characteristics of the bioresource, which limits its application in areas where the statistical data is not available. In addition, GIS methods are static, linear and lack the ability of demonstrating nonlinear feedback structures arising from management policies, anthropogenic activities and practices in harvesting of forest plantations and agricultural farms, and post harvest management of the residues.

Linear programming modelling methods (Akhtari et al., 2014; Shabani et al., 2013; Zhu et al., 2011; Velazquez-Marti et al., 2010), have been used to analyse biomass supply chains and economic viability of energy generation from residues with the aim of minimizing transportation, handling and storage (logistics) costs so that bioenergy systems are economically viable. Muth et al, (2013) utilised integrated multi-factor environmental process modelling and high-fidelity land use datasets to assess the amount of agricultural residue that can sustainably be removed from farm areas in USA. They utilised historical statistical data obtained from government statistics offices to estimate the amount of agro residues produced in farms and project future potential availability of the residues. Their study modelled soil type as a base spatial unit using a national soil survey database. However, linear programming models handle single component analysis of the bioenergy system, either on feedstock supply chain (Mafakheri & Nasiri, 2014; Akhtari et al., 2014; Muth et al, 2013; Sokhansanja et al., 2006) or bioresources conversion processes and technologies economic viability.

Single component analysis of residues-based bioresource production, conversion, economic and environmental aspects, in isolation of the complex interactions of these factors with the components in the primary systems that generate the residues may not give insights of the dynamic behaviour of the poorly developed residues-based bioenergy system over time. As observed in Figure 1.1, the bioenergy system consist of many interconnected and interacting components that are also in continuous interaction with the ecological, economic and social factors, including policies of the sectors in which bioenergy production processes are intertwined. The complexity of sustainable production of residues-based bioenergy needs a modelling approach capable of assessing the complex interlinks of the system structures from residues production to bioenergy allocation to end use processes.

A multi approach assessment of sustainable production of residues-based bioenergy that combines systems approach modelling of bioenergy production, which includes stakeholders' analysis, with the conventional methods of residues to product ratio, onsite residues inventory, bioenergy potential and macro-economic viability evaluation, and a layered five-step sustainability analysis, can provide insights of the state limiting processes and policies to long term availability of the residues supply chains, bioenergy production and reliability of the bioenergy systems. The method can complement the RPR or GIS application in generating valuable information for decision making beyond assessment of quantities of the residues and locating the sites for residues collection and optimum distances to the conversion plants. The systems approach modelling techniques can support evaluation of dynamic behaviour in the bioenergy production value chain over time and provide insights in developing process and policy innovations that can promote sustainable production and mobilisation of the residues for bioenergy production.

2.4 Systems approach modelling based on systems thinking and system dynamics theory

The concept of systems approach modelling in this study is based on systems thinking and systems dynamics modelling methodology (Musango, 2012; Maani & Cavana, 2007; Sterman, 2000; Coyle 1996). The motivation for using systems approach in this research has been introduced briefly in section 1.4. Essentially, system dynamics (SD) modelling methodology promotes systems thinking in analysis of a problem by means of considering the relationships of the components of a system in which the problem is entrenched (Maani & Cavana, 2007). Haines, (2004) has provided the following definition of a system:

> "*A system is a set of elements or components that work together in relationships for the overall objective/vision of the whole*." (Haines, 2004 p11)

Thus, application of the concept of systems thinking to promote sustainable production of primary forest and rice residues-based bioenergy entails understanding sustainability as an outcome of interactions of the components of the system rather than a discrete event happening in one component in isolation of other parts of the bioenergy system. As observed in section 1.2, Figure 1.1, the interaction zone of the different components of the forest and crop residues-based bioenergy system is complex. Therefore, attaining the sustainable bioenergy production interaction zone of the system requires a holistic approach to processes and policy design and implementation that takes into consideration the interactions in the sub systems that form the whole bioenergy system.

2.4.1 Systems thinking theory

Maani & Cavana, (2007 p7) have defined systems thinking as a discipline of study for analysing complex systems through the study of the dynamic behaviour of the systems and the causes and effects over time. Sterman, (2001) states that system thinking is the ability of viewing a problem with a holistic worldview that the problem is being generated in a complex system in which all components are interconnected and in continuous interaction. Sterman, (2001) further argues that single component analysis of the system cannot generate effective process or policy innovations to improve the situation. Jackson, (2003 p3) also, asserts that the concept of systems thinking promotes holism when analysing the performance or behaviour of a system rather than reductionism that focuses on analysis of specific components as being paramount in order to understand the whole. Thus, the concept of system thinking promotes studying a system as a whole within its environment (Jackson, 2003 p340).

Maani & Cavana, (2007 p7), have stated that systems thinking enhances the ability of a modeller to view the big picture of how component parts of a system relate and interact to generate the observable pattern of behaviour/condition over time. Therefore, using the concept of systems thinking in the synthesis of sustainable production of bioenergy from primary forest and rice residues can facilitate holistic assessment of sustainability of the bioenergy systems by incorporating the primary systems that generate the residues. By using systems approach, process operations in primary systems that can be the potential sources of variations (dynamics) over time, can be identified and technological, process and policy innovations to improve undesirable performance of the bioenergy system can be developed. In this study, systems approach modelling enabled applying closed-loop thinking in mapping the residues supply chains by means of tracing the causal-effect relationships consequential of the interactions of the processes, policies and practices in forest plantations management and in rice farms. Specifically, closed-loop thinking enabled analysis of the effects of the processes, policies or decisions on the actual state of residues production and availability for bioenergy production over time.

According to Sterman, (2001), closed-loop thinking differs from open-loop thinking in that open-loop thinking is linear and event-oriented in solving problems. Open-loop thinking does not account for the effects (feedback) of the solutions on the state of the system over a long horizon of time (Morecroft, 2015 p32). Event-oriented thinking to problem solving focuses on short-term results and leads to quick fix solutions to problem solving, which may result in long term negative effects on the system masked between space and time (Morecroft, 2015 p33; Dudley, 2008; Sterman, 2001). Thus, open-loop thinking only treats the symptoms of undesirable situation/condition in a complex system without considering the underlying structures causing the problem.

In contrast to open-loop thinking, system dynamics modelling takes into consideration the effects of alteration(s) in a process or component in the system on the state or desired design objective and performance of the system over time (Sterman, 2001;

Sterman, 2000; Coyle 1996; Goodman, 1974; Forrester, 1968). Therefore, closed-loop thinking is appropriate for synthesis of complex nonlinear systems involving many interconnected and interacting components and sub-systems such as the residues-based bioenergy system presented in Figure. 1.1.

Aspects of linear, event-oriented and closed loop thinking to analysing and solving problems in a system and the differences between the two approaches are presented in Figure 2.1. The gap between the current situation (the situation at hand) and the desired goal of the system in Figure 2.1, defines the problem in the system. In linear open loop event-oriented approach (Fig. 2.1a), the problem is solved as an event and the solution is developed as a fix. The decisions and actions to solve the problem are made in isolation of the interactions between the solution and the components of the system that the solution is intended for and the consequences that can arise from implementation of the solution (Morecroft, 2015 p32; Sterman, 2001).

Closed-loop thinking (Figure 2.1b) takes into account the feedback from the decisions/actions made to solve the problem on the problem and the desired goal over time. In addition, closed-loop thinking enables the modeller to formulate process or policy innovations, test their effects on the system performance and make adjustments in the system processes that are responsible for the dynamic behaviour (Sterman, 2001) to further improve system performance. Furthermore, closed-loop thinking approach allows identification and assessment of the impacts of the problem and the intended solution to solve the problem on the goals of other players in the system and subsystems. The approach also enables assessment of the impacts of solution on other sectors interacting with the system, and the impacts of the actions of these players on the problem and the performance of whole system over time (Sterman, 2001).

Closed-loop thinking also enables analysis of nonlinearities, which are inherent in dynamic complex systems with multiple interacting structures (Sterman, 2001). According to Morecroft, (2015 p22); Coyle, (1996 p132), nonlinearities are disproportionate cause-effect relationships between the action emanating from a process or policy and the resulting behaviour of the system that cannot be represented by linear functions.

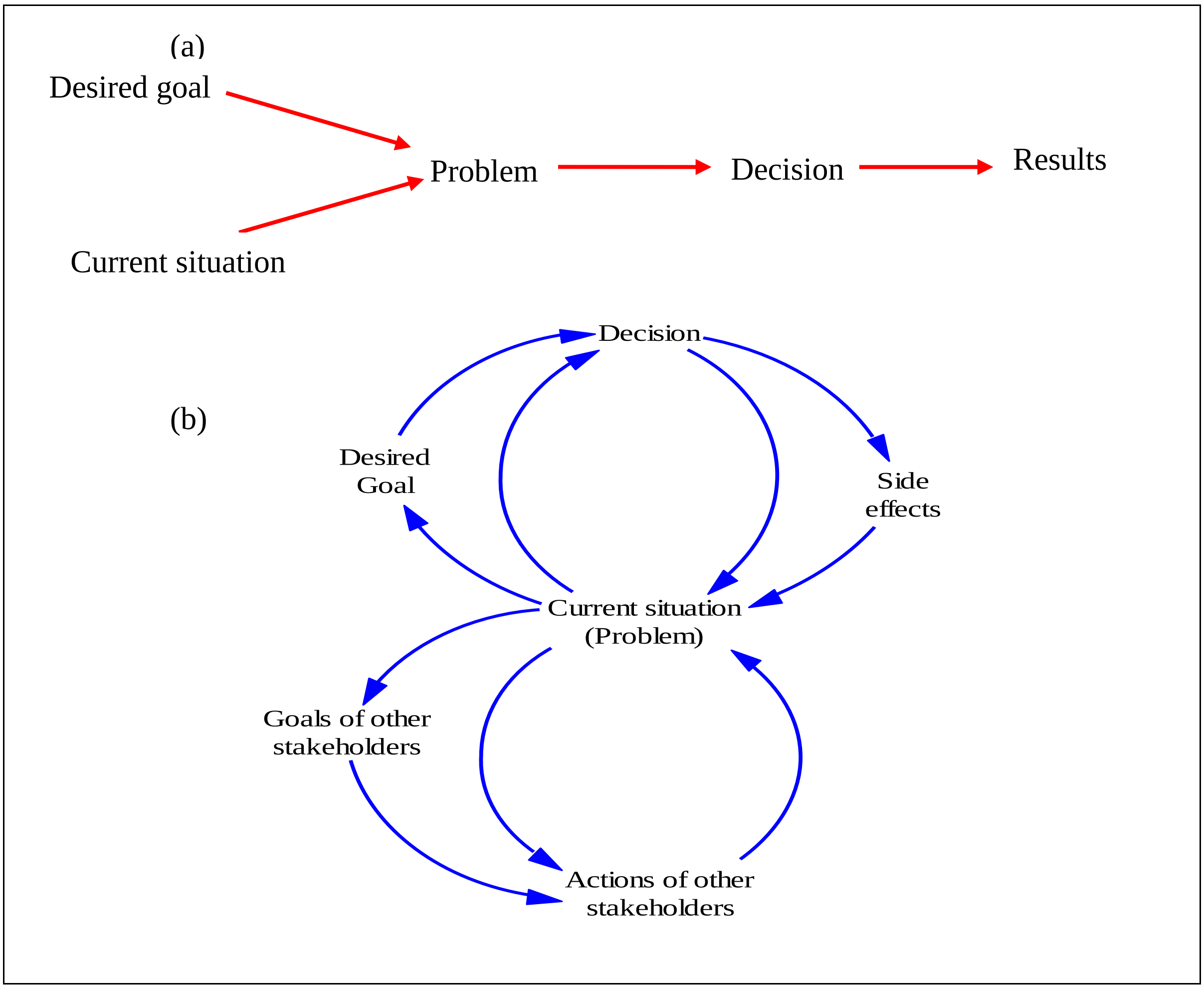

Figure 2.1: (a) Open loop event-oriented approach to solving problems that leads to event-oriented solutions, which does not provide feedback links between the solution and the consequences; (b) Closed loop thinking of problem solving that allows analysing the effects of the solutions intended to solve a problem on the state of the system (adapted and redrawn from Sterman, (2001)).

The goal of systems approach modelling is to improve the undesirable system performance, behaviour, situation or problem and to achieve comparable quality of design performance of a system (Coyle, 1996; Forrester, 1992). Thus, finding a high leverage desirable action, in the form of process, technological or policy innovation, that can minimise or eliminate the discrepancy between the desired goal and the observed (current) condition over a long time horizon is essential in systems approach modelling. While the other modelling methodologies focus only on an ideal future condition for a system, systems approach methodology reveals micro-level structures in a system and how their interconnectedness, interdependency and interactions cause the undesirable state or behaviour/performance in the system, and then the means that lead to its improvement (Forrester, 1992). A synthesis of the system and its internally generated feedback structures, which are intrinsic in complex systems (Park et al., 2014; Sterman, 2000, Senge, 1990, Forester, 1968), provides insights about the causal-effects relationships of the interacting structures, the state limiting processes to attaining the goals of the system and the effectiveness of policies and strategies governing the operation of the system. The goal of sustainability of bioenergy production is to promote production of bioenergy that meets trans-generations energy needs (Brundtland Report, 1987). Therefore, identification of processes that are disenablers to long term availability of primary forest residues for bioenergy production is critical for development of relevant innovative processes and operational policies to promote resilience of the residues supply chains.

Systems approach modelling methodology enables the modeller to develop efficient management strategies necessary for stability of the system (Park et al., 2014; Senge, 1990; Forester, 1968). Furthermore, the systems approach modelling techniques provide opportunity to generate insights that lead to policy formulation for process innovations to attain standard functionality of a complex system (Coyle, 1996; Forrester, 1992) and the means to analysis the causal-effect relationship of the intended alternative solution(s) to a systemic problem on the performance of the system over long time horizon (Maani & Cavana 2007). Therefore, utilising the systems approach in modelling sustainability of primary forest and rice residues-based bioenergy systems can facilitate identification of the state limiting technical processes, policy and operational strategies to sustainable production of bioenergy from the residues supply chains. The approach also can provide opportunity to identify the points or operational strategies that can be enablers to promoting sustainable production of bioenergy based on primary forest and rice residues supply chains as feedstocks.

Variability in forest and rice residues availability and quality over time, and the complexity and high cost of the supply chains have been observed as critical challenges to the development of residues-based bioenergy systems (Akhtari et al., 2014; Ramamurthi, 2014; Delivand et al., 2011). The innovations in forestry and agriculture sectors, where the forest and rice residues are generated, respectively, can have significant implications on availability of the residues respectively. For instance, Sustainable forest management (SFM) is perceived as a more inclusive forest management system compared to sustainable yield management (SYM) (Brandt et al., 2016; Peng, 2000; Luckert, 1997). SFM policy paradigm focuses on ecosystem management including wildlife, water, fish and other resources that depend on the forests for survival while as SYM system aims at maximizing the productivity of the forest sites to obtain high yields of forestry products such as timber and round logs (Brandt et al., 2016; Peng, 2000). However, SFM promotes implementation of partial harvesting of forest stands while leaving behind relatively large quantities of standing trees, snags and dead wood on the harvest site in the forest (Brandt et al., 2016; Peng, 2000). The lack of a benchmark on the proportion of standing trees which need to be left on a mature stand being harvested for timber production may result in intermittent production and unsteady flow of primary forest residues for bioenergy production, especially in regions with limited capacity of forest plantations (≥20 000 ha≤100 000 ha).

Similarly, innovations in the agriculture sector and the debate on conservation agriculture (zero tillage) versus organic agriculture (no or limited chemicals utilisation) (Giller, et al., 2009; Knowler & Bradshaw, 2007), may result in variations in crop yield and residues production, which in turn can result in intermittent bioenergy production and supply to end use processes. As observed by Caputo et al., (2005), energy generation systems require steady flow of fuel (feedstock) to the prime mover for stability, availability, reliability and security of energy supply to end use processes. Therefore, the interconnectedness of the forestry and agriculture sectors to bioenergy systems utilising primary forest and crop resides exacerbates the complexity of sustainable production of bioenergy from these bioresources. Assessment of sustainable production of bioenergy from primary forest and rice residues requires an approach with inherent capabilities of modelling complex system involving many interconnected and interacting structures such as the systems approach based on system dynamics modelling techniques.

System dynamic modelling techniques have been applied in natural resources management including fisheries (Morecroft 2015 p11; Nobre et al., 2009). The approach has also been used in developing models in environmental management and wastewater treatment (Sterman et al., 2013; Chang et al., 2008; Stave. 2003; Guo et al., 2001), energy modelling (Dyner et al., 1995), supply chain management (Angerhofer &

Angelides) and bioenergy systems sustainability assessment and management and bioenergy production (Musango & Brent, 2011; Musango, 2012). However, the approach has not been applied to investigate the potential dynamics and associated impacts in residues-based bioenergy systems to facilitate technological, process and policy innovations in the systems that can promote sustainable integration of the primary systems developed for the production of the principal components (for example, timber and rice), which generate the residues used for bioenergy production, and the secondary (biomass conversion) systems for energy generation. Section 2.4.2 gives the details about the system dynamics modelling tools that make it appropriate for modelling multidisciplinary complex systems such as bioenergy production.

2.4.2 The systems approach model development process

The systems approach model development process involves interacting with key stakeholders in the system under consideration and developing the model, refining it and repeating simulations so that the model behaviour generates confidence to mimic the real world system that the model is representing (Musango, 2012; Maani & Cavana, 2007; Forrester et al., 1976). Consequently, the model development process consists of five distinct but interrelated phases presented in Figure 2.2 (Maani & Cavana, 2007 pp16-18; Forrester, 1992). The phases are further classified into two main interrelated system dynamics approach modelling segments: qualitative mapping/modelling covering phases 1 and 2 and quantitative/simulation modelling for phases 3 to 5 of Figure 2.2 (Vinnix, 2015 p108; Coyle 2000; Wolstenholme, 1999).

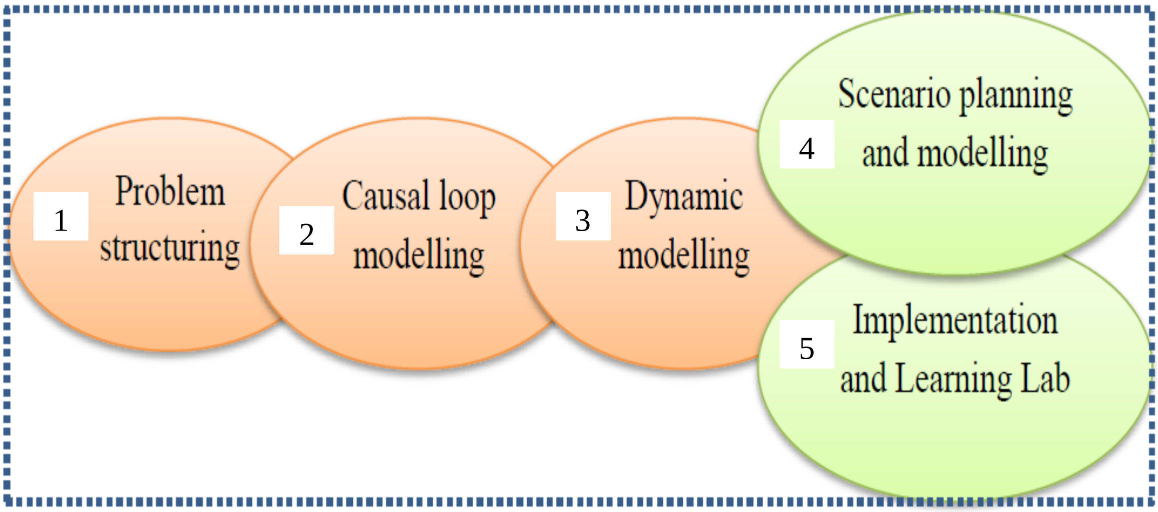

Figure 2.2: The five interlinked phases in dynamic systems approach modelling process. Adapted and redrawn from Maani & Cavana, (2007 p18)

2.4.2.1 Systems approach qualitative modelling

Qualitative modelling involves identifying and describing the problem (phase 1 of Figure 2.2), eliciting stakeholders and their views on the structure and functioning of the system, and their perception of the problem under consideration (Vinnix, 2015 p108, Maani & Cavana, 2007 p23; Wolstenholme, 1999). According to Checkland, (1981), systems approach qualitative modelling enables the modeller to qualitatively capture human and organisational (social) factors influencing and/or influenced by other factors in the system under consideration to generate the pattern of undesirable behaviour or performance of the system. These social factors may not be adequately assessed using quantitative programming models. Vinnex, (2015 p108); Coyle, (2000) have asserted the usefulness of qualitative mapping in providing comprehensive description of a problem and its potential causes and solutions that culminates into a visual representation of the problem in the form of a causal loop or a stock and flow diagram (phase 2 of Figure 2.2). Thus, qualitative modelling of sustainable production of residues-based bioenergy can enable the modeller to provide a holistic description of the system structures at play from production of the residues to energy generation and visually demonstrate how both qualitative and quantitative factors interrelate as enablers or disenablers to sustainability of the bioenergy system.

Many approaches used for the assessment of availability and bioenergy potential of forest and crop residues, presented in sections 1.3 and 2.2, suffer limitations of incorporating qualitative and quantitative factors in the model framework, and inability to visually demonstrate their relationships. These limitations may lead to poor understating of the system structures which can be the liming factors to sustainability of residues-based bioenergy production when the approaches are used to inform process and policy formulation. As observed by Sterman, (2001); Forrester, (1968), poor understanding of the structures responsible for the dynamic behaviour in systems may result in formulation of ineffective process and policy innovations to solve the problem.

Therefore, using the systems approach for modelling sustainable production of primary forest and rice residues-based bioenergy can provide the opportunity of assessing sustainability of the bioenergy system holistically by incorporating the human and organisation factors in the model, from production processes of the principle components that generate the residues to bioenergy allocation to end use processes, besides quantitative variables in the value chain. The systems approach can provide useful insights and better understanding about the fundamental structures in the whole residues-based bioenergy production value chain and how these structures influence each other when compared to single component analysis. In addition, the use of causal loop/influence diagrams in system dynamics approach modelling, to show the interconnectedness and type of influence between variables, provides the opportunity to visually demonstrate the interconnectedness of the structures that are at play in the whole residues-based bioenergy value chain by means of causal loop diagrams.

2.4.2.2 Eliciting system structures using causal loop diagrams (CLD)

The main focus of system dynamics modelling is the structure and behaviour of a system (Goodman, 1974). The structures of a system consist of sets of interconnected variables that are in continuous interaction thereby influencing each other to generate the observable pattern of behaviour or performance of the system (Pruyt, 2013; Goodman, 1974). From the system dynamics perspective, a variable is an action, a condition, decision, and/or a situation in the form of material, information, or social issue that can influence and can be influenced by the other factors interacting with it in the system (Maani & Cavana, 2007; Coyle, 2000; Sterman, 2000; Coyle, 1996; Senge 1990; Goodman 1974). The sets of interacting variables are interlinked by means of arrows to form feedback loops, presented as causal loop or influence diagrams to demonstrate their interconnectedness and how they influence each other to generate the undesired system behaviour or performance over time (Pruyt, 2013; Maani & Cavana, 2007; Coyle, 2000; Sterman 2000; Coyle, 1996; Goodman, 1974; Forrester, 1968).

Causal loop diagrams are useful for mapping the structures of a complex system as a whole in order to identify the sources and level of influence of the undesirable complex dynamic behaviour of the system over time, and to develop strategies that can steer the system towards more desirable performance (Pruyt, 2013). Maani & Cavana, (2007), have pointed out the inherent capability of incorporating both qualitative (soft) and quantitative variables in causal loop diagrams as one of the effectiveness of the systems thinking approach in modelling multidisciplinary complex systems.

According to Maani & Cavana, (2007 p28), the fundamental elements of a causal loop diagram include the variables and arrows. The arrow of a causal loop is defined by an arrow head that indicates the direction of influence and polarity (positive or negative) at the arrowhead that indicates the type of influence by the variable at the tail of the arrow on the variable at the arrowhead. When two or more causal links are connected in such a way that the causality of a variable in the loop can be traced back to the same variable through the links then the links form a feedback loop (Pruyt, 2013). Figure 2.3 shows a basic example of a causal loop diagram of the interactions btween variables X and Y.

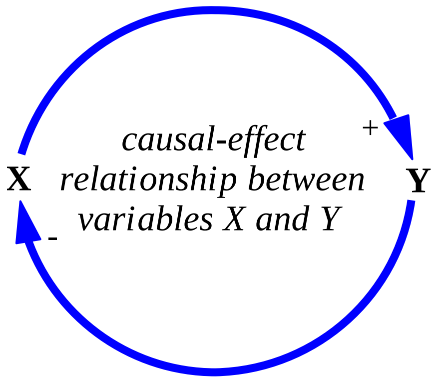

Figure 2.3: A causal loop diagram of the interconnectedness and interactions between variables X and Y in a system

As stated by Maani & Cavana, (2007); Sterman, (2000), Goodman, (1974), the positive polarity (+) at the arrow head in a causal loop diagram indicates that the variable at the arrowhead changes in the same direction as the variable at the tail of the arrow (positive correlation) while as, the negative polarity (-) indicates that the variable at the arrowhead changes in opposite direction of the change in the variable at the tail of the arrow (negative correlation). For example, in Figure 2.3, the polarities indicates that an increase/decrease in X causes an increase/decrease in Y while as an increase/decrease in Y causes a decrease/increase in X.

Coyle, (2000, 1996); Sterman, (2000); Wolstenholme, (1999); Goodman (1974) have shown that causal loop or influence diagrams are models formulated by using variable names connected by links to represent and provide qualitative analysis of a real system. In addition, the causal loop diagrams offer a convenient means of representing interconnected structures of a complex system that are influencing the behaviour of the system before developing the model equations and a quantitative/simulation model (Sterman, 2000; Wolstenholme, 1999; Goodman, 1974). Coyle, (2000) has further argued that a rigorous and well-organised description of the structures and accurate identification of feedback loops in the causal loop diagrams of the system under consideration is a precursor to quantitative system dynamics approach modelling. Therefore, causal loop diagrams can be used to describe and visually demonstrate qualitatively the structures and feedback loops at play in primary forest or rice residues-based bioenergy systems that can be the disenablers to sustainability of the systems.

2.4.2.3 Systems approach quantitative modelling

The second segment of dynamic systems approach modelling involves translating the qualitative description of the problem being modelled into a quantitative simulation model (Forrester, 1992). Smith, (2000) has asserted the need for quantitative simulation of complex nonlinear systems beyond qualitative mapping using influence (causal loop) diagrams for more rigorous analysis of the systems. Quantitative simulation of a complex nonlinear system in the SD modelling approach is achieved by identifying the stocks and flows relationships that are involved in the system, writing the stocks and flows equations that define the relationships and converting these to a simulation model (Ahmad & Simonovic, 2000; Forrester, 1992).

In system dynamics modelling, stocks or levels are variables that accumulate or get depleted within the system as a result of the interactions between these variables and the other variables in the system over time (Maani & Cavana, 2007 p64; Sterman, 2000; 2001; Ahmad & Simonovic, 2000). For example, water in a bathtub is a stock that accumulates when water flowing into the bathtub (inflow) is more than the water flowing out (outflow) and depletes when the outflow is higher than the inflow (Sterman, 2010; Sweeney & Sterman, 2000). On the other hand, flows or rates are variables that cause variations in the stocks by increasing or decrease the quantities of the stocks (Maani & Cavana, 2007 p64; Sterman, 2000; 2001; Ahmad & Simonovic, 2000). In the bathtub example, the inlet and outlet valves regulate the rate at which the level of water in the bathtub increases or decreases per unit time (Sterman, 2010; Sweeney & Sterman, 2000).

According to Sterman, (2010; 2000); Maani & Cavana, (2007), flow variables are the outcomes of management decisions or external forces exerted on the system that alter the levels of stock variables, which may not instantly be observable except through accumulation or depletion of the stocks in the system. Forrester, (1992), has stressed that the process of writing stocks and flows equations reveals the gaps in the qualitative description of the system structures that need to be corrected thereby enabling the modeller to make the system description and hypothesis explicit. Therefore, by using the dynamic systems approach to develop a model for sustainable production of bioenergy from forest and rice residues, this research reveals the key stock variables and the operational policies, management decisions and external factors as flow variables that can alter the levels of the stock variables in forest plantations management, rice farming, bioenergy production and bioenergy allocation to end use processes. In addition, systems approach modelling can reveal the interrelationships of the stocks and flows variables that can be the sources of the dynamic behaviour and the limiting factors to sustainability of the primary forest or rice residues-based bioenergy systems.

Besides the stocks and flows variables, SD simulation models also consist of auxiliary variables or converters which are intermediate variables that can be substituted in flow equation (Pruyt, 2010, Maani & Cavana, 2007). The auxiliary variables play a significant role of enabling the modeller to simplify complex flow equations and facilitate understating of the relationships of the variables responsible for the undesirable system performance or behaviour over time (Maani & Cavana, 2007). The SD model auxiliary variables also include constants, time delays between management decision/action and the consequences emanating from the decision/action and the graphical and behavioural relationships in the system (Pruyt, 2010). Thus, both systems approach qualitative and quantitative modelling of sustainable production of residues-based bioenergy production can provide the opportunity to identify state limiting structures, including time delays prevalent in the whole systems from residues production to energy allocation to end use processes.

2.4.3 Limitation of dynamic systems approach modelling techniques

Systems approach modelling techniques are used to gain understanding of system behaviour overtime (Duggan, 2016). The techniques primarily focus on simulation models that provide conditional, imprecise projections of dynamic behaviour of the system over time (Duggan, 2016; Pruyt, 2010). As observed by Pruyt, (2010), the simulation results of the dynamic systems approach models are interpreted qualitatively as general modes of behaviour wherein the univariate and multivariate sensitivity analyses are mainly undertaken for validation of the model and not exploration. The dynamic systems approach models are not for absolute, precise, point or trajectory prediction or conditional precise predictions (Duggan, 2016; Pruyt, 2010; Sterman, 1987). Therefore, systems approach modelling techniques cannot be used for absolute optimisation of the scale of the conversion plant, the radius for feedstock collection from the conversion plant or precise predictions of profitability of the bioenergy system like econometrics, mathematical linear programming or discrete event simulation models. Furthermore, systems approach modelling techniques are mainly used in social and business systems involving many social variables which cannot be predicted in absolute terms.

However, despite these limitations, the dynamic systems approach modelling techniques provide insights of points of high leverage in the system being analysed where small changes can result in significant improvements in the performance/behaviour of the system over time (Musango, 2012; Sterman, 2000; Coyle, 1996; Forrester, 1968). Therefore, systems approach modelling of sustainable production of bioenergy from primary forest or rice residues can provide insights of the enablers and disenablers in the residues value chains that require technical, process and/or policy innovations, which can promote sustainable production of the residues-based bioenergy. In-depth understanding of the components and structures of the primary forest or rice residues-based bioenergy system, from feedstock production in forest plantations or rice farms to energy generation and allocation to end use processes is essential as a precursor to the application of the systems approach to modelling sustainable production of residues-based bioenergy. Forest plantations and rice farming management systems need to be understood in order to develop relevant process and policy innovations that can support sustainable production of bioenergy from the forestry or rice residues.

2.5 Linking forest management systems and primary forest residues-based bioenergy production

Forest plantations are potential sources of feedstock (forest residues) for bioenergy production. The innovations in processes and technologies for converting these bioresources to modern forms of energy provide opportunity for efficient utilisation of primary forest residues for generation of heat, electricity, liquid biofuels and biochemicals to meet the energy needs of various end use processes (Goyal et al. 2008; Ji-Lu, 2007; McKendry, 2002b; Demirbas, 2001; Bridgwater et al., 2001; Küçüki & Demirbas, 1997). However, management and harvesting systems of forest plantations vary based on the development objectives of the plantations. Roux at al., (2005); Chamshama et al., (2009); Chamshama & Nwonwu, (2004); Mwendera, (1994) have observed that management and harvesting systems of forest plantations established in developing countries like Malawi, where indigenous tree species characterised by slow growth rates have been felled and replaced with fast growing exotic tree species, vary between plantations, within and across the countries.

Management and harvesting systems of forest plantations in developing countries depend on the development objectives of the plantations, ownership and socio-economic spectrum of the stakeholders participating in the forest plantations value chains. For instance, Chamshama & Nwonwu, (2004); Kafakoma & Mataya (2009) have presented some forest plantations established for energy production in Ethiopia and Senegal, timber production in Malawi, and for industrial and pulpwood in South Africa and Congo. Introduction of new forest product assortment has been highlighted by Richardson et al., (2002 p69) as the contributing factor to the increase in scope and complexity of forest management systems, and policy innovations in forest management.

Forest management systems such as sustainable yield management (SYM) system (Peng, 2000; Luckert, 1997), sustainable forest management (SFM) system (Brandt et al., 2016; Peng, 2000), full protection, low-intensity, intensive and super-intensive management (Carmean, 2007; Messier et al., 2003) have been suggested in literature. Sustainable yield management aims at maximizing the productivity of the forest sites to obtain high yields of forestry products such as timber and round logs (Peng, 2000; Luckert, 1997). On the other hand, the main objective of sustainable forest management system is to achieve multiple benefits, including forest protection, biodiversity conservation and income enhancement (Brandt et al., 2016; Peng, 2000). SFM policy paradigm focuses on ecosystem management including wildlife, water, fish and other resources that depend on the forests for survival by promoting partial harvesting of forest stand (Brandt et al., 2016; Peng, 2000).

Full protection forest management refers to management system where logging is completely banned (designated no-cut reserves) in the section of the forest, whereas low-intensity management is similar to ecosystem forest management in which partial harvesting is allowed while relatively large quantities of standing trees, snags and dead wood are left in the forest after harvesting (Carmean, 2007; Messier et al., 2003). Consequently, the forest management system practiced in a specific plantation may influence the stocks of primary forest residues over time. Availability of the residues may also vary between forest plantations based on the harvesting systems associated with a particular management system practiced in a specific plantation. Therefore, onsite assessment of management and harvesting systems in the plantations can provide insights of potential impacts that the management and harvesting systems may have on long term availability of primary forest residues and sustainability of bioenergy systems utilising the residues for feedstock.

2.6 Linking rice production systems and rice residues-based bioenergy production

Rice is a universal food crop for both rural and urban households in developing and developed economies. The production of rice in rice farms provides food for human consumption and residues (rice straws and husks), which are potential feedstock for bioenergy production. Kadam et al., (2000) have stated that 1.35 tonnes of rice straws are generated for every tonne of processed rice grain. Large quantities of rice straws are left in the field after harvesting while husks are left at the processing mills after processing the paddy into grain (Zalengera et al., 2014; Gadde et al., 2009; Kadam et al., 2000). Open fire burning of these bioresources is perceived to contribute to emission of 6.7t/ha of CO_2 (Kadam et al., 2000) while natural decomposition would contribute to CH_4, emission, besides CO_2, into the atmosphere (Gadde et al., 2009), which is 21 times more potent than CO_2 on influencing global warming. Thus, rice residues-based bioenergy production has positive contribution to increasing the portfolio of energy from renewable resource and mitigation of greenhouse gas (GHG) emissions.

Rice farming is a resource intensive system. Rice is cultivated in water flooded and mostly rain-fed lowland areas with rainfall of about 700 mm to 2000 mm per cropping season. For instance, Gadde et al., (2009), have observed that 45% of the global land used for rice production relies on rain-fed cultivation. As a result of the high water requirement, irrigation of rice farms for dry planting is also energy intensity (Chapagain & Hoekstra, 2011; Adeniran et al., 2010). Therefore, the constraints of water, energy and suitable arable land for rice production can result in low rice yields and rice residues throughput per farming season, which in turn can limit the benefits of the food and rice residues-based bioenergy value chains.

According to Gallagher et al., (2003), the amount of rice straws available for bioenergy is also constrained by an increase in demand of the straws for animal feed as a result of increased animal population. The amount of rice straws for animal feed is evaluated as a product of animal population and the daily animal feed requirement while annual animal feed requirement is estimated from annualized daily animal feed requirement excluding the portion of the year when animals graze on green pasture (Gallagher et al., 2003). The quantities of straws utilised for animal feed and other competing uses can result in variations in the amount of residues that can be available for bioenergy production over time. Therefore, process and policy innovations in deployment of rice residues-based bioenergy which can be supplied to state limiting processes in the rice production value chain to promote rice production, can enhance food security and increase availability of the rice residues for bioenergy production. In addition the interrelationships of the components of the bioenergy systems and the structures in the rice farming system that generates the rice residues, and the state limiting structures to sustainable production of bioenergy need to be understood.

2.7 Resilience of bioresource supply chain as sustainability criterion for residues-based bioenergy systems

A bioenergy system is a functioning unit of distinct components connected and interacting together for generation of energy from bioresources. The components of a bioenergy system based on forest or rice residues, and the intertwinement and interactions of the system with the economic, environmental and social factors, and the policies of forestry, agriculture and energy sectors have been presented in Figure 1.1 in Chapter 1. The bioenergy system consists of three main components (subsystems) that include: (i) the bioresource supply chain; (ii) the bioresources conversion process and technology; and (iii) bioenergy and co-products allocation to end use processes. As observed by Buchholz, (2007); Sims, (2002); McKendry, (2002); Demirbaş, (2001), the choice of the conversion route and technology for energy generation from bioresources depends on the amount and characteristics of the bioresources and the forms of energy needed by the end users.

The value chains of the bioresources (primary forest and rice residues) have been discussed in the previous sections 1.6 and 2.2 in Chapter 1 of this dissertation. The development objectives of bioenergy production and the choice of conversion routes and technologies for converting forest and rice residues to bioenergy have focussed on environmental, economic and social factors as sustainability indicators. For instance, mitigation of the effects of global warming by reducing greenhouse gas emissions, impacts on ecosystems and land use, economic viability (profitability) of the bioenergy project and social impacts such as creation of direct and indirect job, and enhancing cohesion of the local communities have been extensively investigated and used as sustainability indicators of bioenergy systems (Buchholz & Volk 2012; Zhou et el., 2011; Haberl et al., 2010; Buchholz et al., 2009; Lewandowski & Faaij). However, resilience of the sources of residues as a sustainability criterion for bioenergy systems utilising residues-based feedstock supply chains, and approaches to deployment of the residues-based bioenergy systems that can promote resilience of the residues supply chains, have not adequately been assessed.

Resilience of the residues supply chain has been defined, in the context of this study, as the steady production, availability and reliability of supply of sufficient amount of the residues for bioenergy production to meet the design feedstock requirement of an optimum bioenergy conversion plant scale over time. Steady supply of energy resource to a prime mover in energy generation promotes reliability of the energy system and security of energy supply to end users (Munoz-Hernandez et al., 2013 p18; Moriarty & Honnery, 2007). Therefore, intermittent production, availability and supply of the residues to a conversion plant can result in intermittent production and supply of bioenergy to end use processes. Intermittent supply of the bioenergy to end users can erode energy end-users' perception of reliability of the bioenergy to meet their energy needs. In addition, bioresource conversion plants designed and sized based on intermittent feedstock supply chains may scout for feedstock from unsustainable sources. Innovations in operational processes at points of high leverage in forest and rice residues production and supply that can promote resilience of the residues supply chains are essential for sustainable production of bioenergy from the residues.

2.8 Scale of operation and deployment strategies of bioenergy systems

Bioenergy systems are developed as large scale centralised grid connected or small scale decentralised modular systems (He et al., 2013; Mahapatra & Dasappa 2012). According to McKendry, (2002), the scale of the conversion plant depends on the amount of bioresources available in an area. Brigwater et al., (2002); Dornburg & Faaij, (2001), have pointed out the effect of the scale of a conversion plant for biomass to electricity on overall system efficiency, specific and generation cost of electricity. These studies show low generation cost of electricity (GCOE) for large scale and mature technologies (technologies that have no learning curve when deployed). However, small-scale biomass conversion plants, developed near the points where bioresource feedstocks are produced, provide opportunity of developing short feedstock supply chains (Bocci et al., 2014; 2013).

Cameron et al., (2007); Sokhansanja et al., (2006) have pointed out that a large proportion of operational costs of a bioenergy system is linked to the feedstock supply chain and plant capacity. The feedstock cost is made up of two main components: the distance variable costs (DVC), incurred by hauling the feedstock to the conversion plant and the distance fixed costs (DFC), consisting of the fee paid for the feedstock (cost price) per tonne and the labour cost for loading and offloading feedstock transporting trucks (Cameron et al., 2007). Developing bioenergy systems near the source of feedstocks offers the advantage of sourcing the feedstock with low distance variable costs (Bocci et al., 2013). In addition, locally produced residues-based feedstock supply chains to small-scale bioenergy systems, located near the source of the residues, and where the energy products are supplied to residues producers and mobilisers, can provide the opportunity of decreasing the distance fixed costs.

Location of small-scale bioenergy systems in rural communities surrounding the Viphya forest plantations and in the rice farms (near primary forest and rice residues producers and mobilisers, respectively) in Malawi can provide the opportunity of developing bioenergy systems with low operational costs. As observed by Cameron et al., (2007), operational costs contribute significantly to generation cost of electricity (GCOE) over time. A review of small-scale biomass combustion and gasification conversion routes and technologies has been provided in section 2.9 of this dissertation.

2.8.1 Electricity generation, supply and access in Malawi

Electricity generation in Malawi is hydro-based (Kaunda, 2012). Hydro power plants account for 98% of the total electricity generation capacity, which was at 352 MW at the time of this study in 2015 (Zalengera et al., 2014). The supply of electricity to rural areas in Malawi, like in most developing countries, is limited to extension of the national grid from the centrally controlled grid systems through rural electrification programmes (Kaunda, 2012). Extension of the national grid to rural communities is marred by low investment in the grid infrastructure, which results in large proportion of the population not accessing grid electricity (Urpelainen, 2014; Zalengera et al., 2014; Hiremath, 2009; Kirubi, 2008). In Malawi, for instance, low electricity generation capacity and limited investment in new power plants and grid infrastructure limit expansion of the grid and access to grid electricity by the rural communities (Zalengera et al., 2014). Figure 2.4 shows the trend of population growth in Malawi, electricity generation capacity and electricity access over a time horizon of 60 years. Zalengera et al., (2014); Kaunda, (2012); Openshaw; (2010) have observed that 85% of the population in Malawi is rural based. This stratum of the population depends on subsistence rain fed farming for livelihood and only 1% have access to grid electricity.

The increase in population over time has increased the proportion of the rural population without access to electricity (Fig. 2.4). Thus, deployment of primary forest and rice residues-based bioenergy in small-scale decentralised systems at rural community level near the source of the residues and the energy demand can facilitate access to modern forms energy, such as electricity, in rural communities. Electricity supplied to the communities can be utilised for powering state limiting processes and reduce the social inequality that emanates from the lack of access to modern forms of energy.

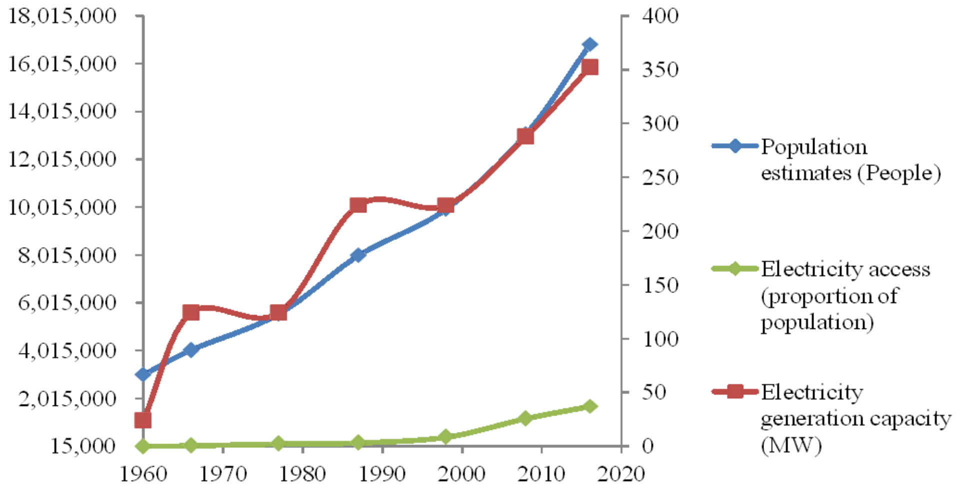

Figure 2.4: The trend of growth of population from 3 million to about 16 million, electricity generation capacity from 24 MW to 352 MW and electricity access from 1% to 10% of the population over a period of about six decades (1960 – 2016) in Malawi (Population growth extrapolated from Malawi Population and Housing Census, (2008) Report and Energy generation capacity and access obtained from Zalengera et al., (2014).

The deployment of small-scale decentralised bioenergy systems utilising forest or rice residues is a well known concept. Decentralised biomass to electricity generation systems is perceived to support the development of rural areas in developing countries with similar conditions to Malawi (Kirubi, 2008; He et al., 2013; Hiremath, 2009). However, previous studies (Delivand et al., 2011; Buragohain et al., 2010; Siemons, 2001) mainly have assessed techno-economics and social aspects of the concept as event oriented and linear components. The emphasis on econometrics modelling of bioenergy technologies is based on assumption of the influence of economic implications of the technologies on the rate of development and uptake of the technologies (Bridgwater 1994). As a result, there is lack of strategic information on resilience of the feedstock supply chain against the changes in processes and operational policies in the systems. Therefore, the systems approach modelling techniques, reviewed in section 2.2.3, can be utilised to assess sustainability of small-scale decentralised residues-based bioenergy system.

Systems approach modelling techniques have not been tested in assessing sustainability of residues-based bioenergy systems to promote integration of bioenergy systems and the forest and rice farming systems that generate the residues in order to promote sustainable production of bioenergy and the principal components in the primary systems. As observed in section 2.3, the systems approach modelling techniques have inherent capabilities to reveal the complex interactions between the components of the small-scale residues-based bioenergy systems. In addition the approach can provide insights of the dynamics resulting from the interrelationships between the processes, the key stakeholders, the form of energy and supply options of the energy to the stakeholders, and other variables in the systems that together, rather than in isolation can promote sustainable integration of bioenergy production in the forest plantations and rice farms in Malawi.

2.9 Conversion of primary forest and rice residues to bioenergy in small-scale bioenergy production systems

Thermochemical processes and technologies have been used for conversion of primary forest and rice residues for energy generation over the years. This section covers a review of three thermochemical conversion processes of primary forest and rice residues and the forms of energy and energy carriers that are generated. The aim is to inform the selection process of the conversion route and technology for small-scale decentralised bioenergy systems that can sustainably be supplied with the locally generated primary forest or rice residues in rural communities. Figure 2.5 shows the thermochemical conversion routes of biomass to electricity considered in this study.

2.9.1 Direct combustion of primary forest and rice residues to heat and electricity

Direct combustion of biomass is a rapid thermochemical reaction of biomass and oxygen by direct burning of the biomass in air at temperature ranges of about 800 ^{o}C and 1000 ^{o}C (Brown, 2011 p5; van Loo & Koppejan, 2008 p7; McKendry, 2002b). The chemical energy stored in the biomass is converted into useful energy in the form of heat and electricity (McKendry, 2002b). The theory of biomass combustion to heat or electricity or a combination of both, and the configuration of the systems have been presented widely in previous studies and literature (Brown, 2011; Bridgwater et al., 2002, 1994, Sims, 2002; van den Broek, 1996) and it is not part of the scope of this study.

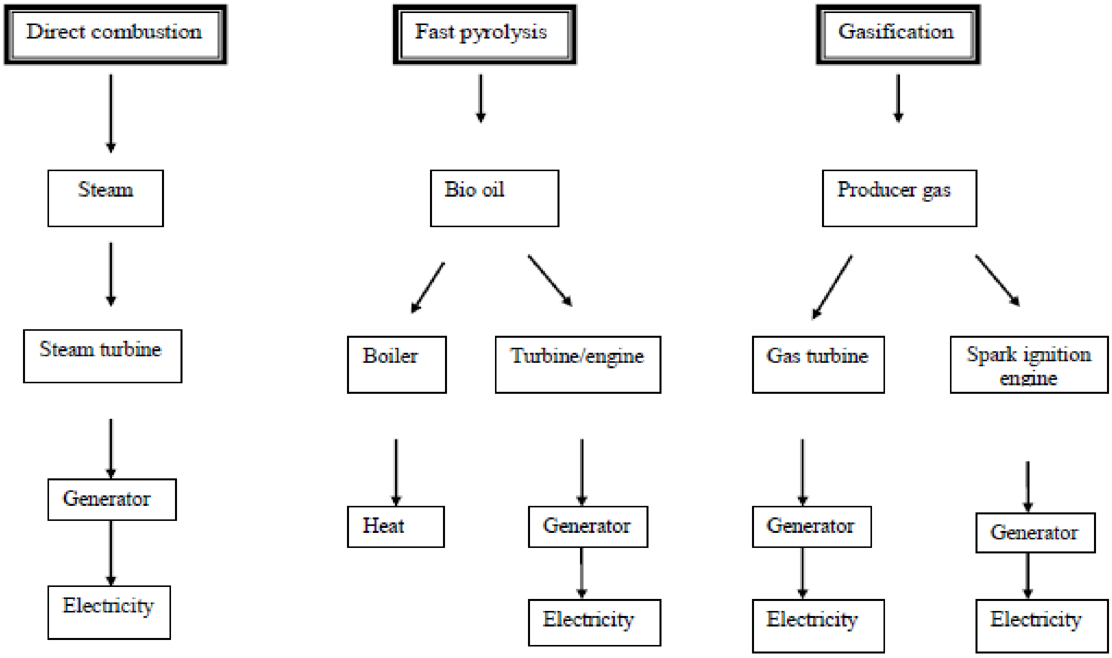

Figure 2.5: Thermochemical conversion routes for conversion of primary forest and rice residues to electricity (Redrawn from The German Solar Energy Society (DGS), Ecofys, (2005) with minor modification)

Technologies for direct combustion of biomass to heat and electricity are well developed (mature technologies), have been used for energy generation for many years (adequate experience of operating the technologies) and can be developed in a wide range of scales from small-scale for household or community energy supply to large scale systems connected to the grid network (Brown, 2011; van Loo & Koppejan, 2008 p4; McKendry, 2002b). Generation of electricity in direct biomass combustion systems involves the burning of the biomass in boilers to generate steam that powers a steam turbine, which is coupled to a generator that converts the mechanical energy into electrical energy.

Bioenergy system developers need strategic information for decision making on the scale of the bioenergy system generating the energy through direct combustion of biomass (van Loo & Koppejan, 2008). Figure 2.6, adapted from (van Loo & Koppejan, 2008), shows the factors that influence the design of a biomass combustion system for a specific project site.

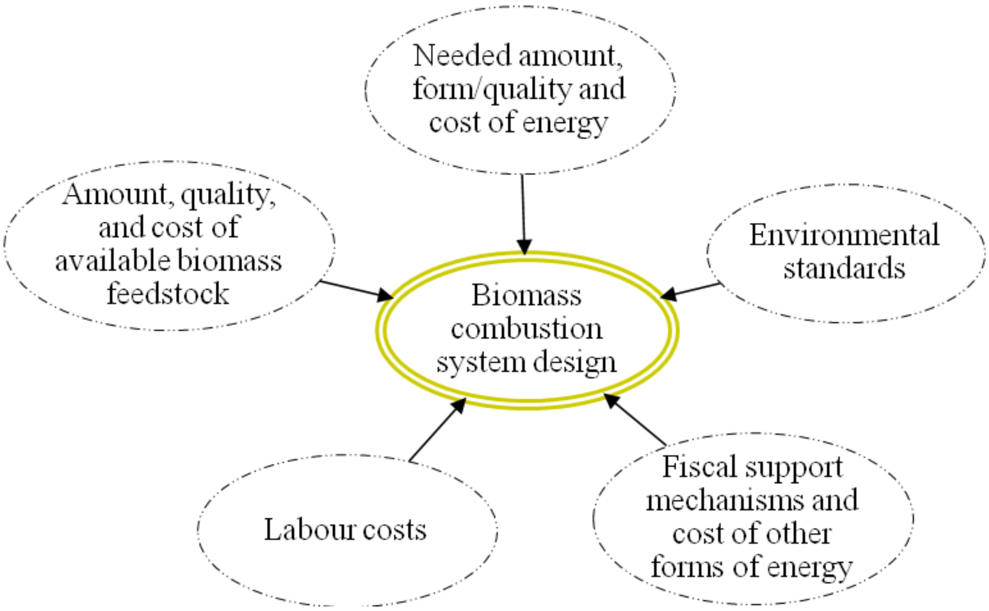

Figure 2.6: key influencing parameters to the design of biomass combustion systems (adapted and redrawn from van Loo & Koppejan, (2008 p4))

Thus, specific site assessment of the variables in the design parameters of a direct combustion biomass system can provide insights of the tradeoffs and tolerance between the scale of the system and generation cost of energy (GCOE) for energy supply in rural and low income communities.

Studies have shown that the efficiency of direct combustion systems, the cost of feedstock and GCOE vary with the scale factor of the conversion plant (Bridgwater, 2002). Table 2.1 shows differences in the key design parameters of the biomass combustion system between large scale and small scale systems. The interconnectedness of these structures in residues-based bioenergy systems and the interactions that may result from the interdependency and interactions between the structures need to be understood by investors and developers of direct combustion systems of primary forest and rice residues for bioenergy production.

Table 2.1: Comparison parameters between large and small-scale biomass combustion systems

Parameter	**Large scale biomass combustion system**	**Small-scale biomass combustion system**
Fuel quality	Can utilise low quality fuel	Requires high quality fuel
Fuel quantity	Large amount of fuel	Scale can be matched with available fuel with the potential of modular deployment.
Fuel cost (at the gate)	High cost due high transport costs of hauling large amounts of feedstock	Low cost
Efficiency	High (24 – 40%)	Low (10 – 24%)
Generation cost of energy	Low	High

2.9.2 Pyrolysis of primary forest and rice residues to bio-oil

Pyrolysis is a thermochemical conversion process of biomass in the absence of an oxidant at elevated temperatures to produce liquids, gases and char (Brown 2011; (Brown, 2011 p7; McKendry, 2002b). Singh & Gu have presented four type of the pyrolysis process which include: 1) conventional pyrolysis, 2) slow pyrolysis, 3) fast pyrolysis and 4) flash pyrolysis. Brown, 2011; Qi et al., (2007); Ji-lu, (2007), have shown that fast pyrolysis (a rapid thermal decomposition of organic compounds in the absence of oxygen) is an effective bioresource conversion process with high liquid oil yield of about 70 to 80% of the overall pyrolysis products and high bio oil to feedstock ratio. Figure 2.7 shows a simplified architectural layout of pyrolysis plant for conversion of biomass to bio oils (adapted from (Basu, 2010 p69). Converting the primary forest and rice residues to bio oils using fast pyrolysis can be an effective way of utilising these bioresources. However, utilisation of bio oils in engines to generate electricity currently faces some challenges due to the physiochemical properties of the bio oils.

Bio oils have strong acidity (pH of 2.5) resulting from carboxylic acids, high moisture (15-30%), oxygen (35-40%) and distillation residues (50%) content than the conversional fuels (Qi et al., 2007). The reactivity of the oxygenated groups in the bio oils result into unstable characteristics of the oils in storage and during combustion (Demirbas, 2010 p171). The viscosity of bio oils also changes over time while in storage. In addition, high acidity makes bio-oil very corrosive and particularly critical at high temperature, which in turn imposes additional costs on construction materials of the storage and utilisation vessels, and the upgrading process before using the bio-oils. Unlike direct combustion of biomass, which can utilise heterogeneous feedstocks, pyrolysis requires comminution of feedstock into specified sizes.

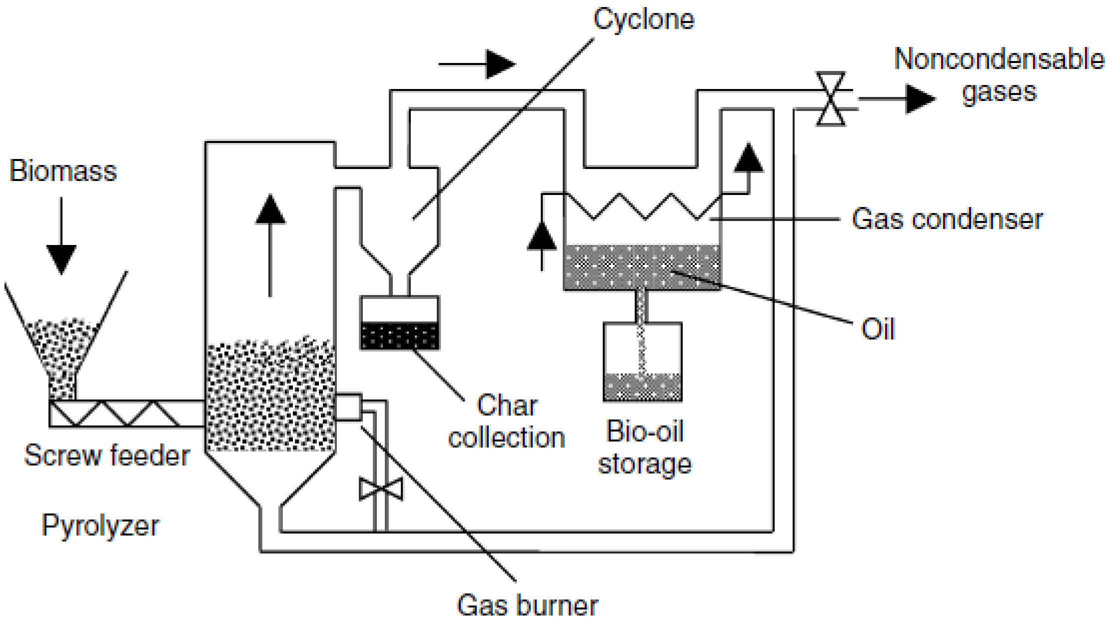

Figure 2.7: Simplified schematic of pyrolysis plant for conversion of biomass to bio oils (adapted from (Basu, 2010 p69)

Ji-lu, (2007) analysed the physical properties, chemical composition, stability, miscibility and corrosion of bio-oils from rice husks. They found that bio-oil stored at 60 degrees Celsius resulted in loss of weight of about 0.6% and 1% for copper (Cu) and stainless steel strips when kept in the bio-oil for 128 hours, respectively. These results indicate that the bio-oils from rice husks would cause mild corrosion of copper and steel used as vessels or storage facilities of the oil. The study also observed that the viscosity of bio-oils increased with increasing storage time as a result of slow polymerization and condensation reactions. However, the viscosity of a liquid fuel is an important parameter in the design and operation of the fuel injection system, as well as on the atomization quality and subsequent combustion properties of the fuel (Qiang et al., 2008). Variability of the viscosity of bio oils with temperature is a limiting factor to the wide application of bio oils as a substitute of fossil diesel in diesel engines.

Pyrolysis bio-oil is also immiscible with fossil diesel (Ji-lu, (2007)). Although a homogeneous emulsion formed when bio-oil is mixed with fossil diesel depicts improved physical properties of high heating value, lower pH and lower viscosity than the bio-oil (Ji-lu, 2007), with the potential of application in diesel engine for the generation of electricity, its application has not been tested at practical scale beyond laboratory tests. The lack of maturity of technologies for direct application of pyrolysis bio oils can exacerbate the challenge of using bio-oils from primary forest and rice residues singly or as a co-firing fuel with fossil diesel in small-scale decentralised bioenergy systems for rural energy supply which may increase operational and maintenance (O&M) costs of the system. O&M has a direct correlation with GCOE and the price of energy paid by end users.

2.9.3 Gasification of primary forest and rice residues to electricity

Gasification is a thermochemical process in which biomass is converted into combustible gas mixture of CO, H_2, CH_4, CO_2, N_2 and small quantities of hydrocarbons (producer gas) by partial oxidation at elevated temperatures of 800 to 900 ^oC (Brown 2011 p47; Basu, 2010 p117; McKendry, 2002). The producer gas from gasification of biomass contains 60 to 90% of all the energy contained in the original biomass and can be used in spark ignition engines or gas turbines for generation of heat and electricity or processed further to syngas or synthetic liquid (Brown 2011; McKendry, 2002b; Reed & Das, 1988).

According to Brown, (2011 p68); McKendy, (2002b); Reed & Das, (1988) biomass gasification is a commercially proven technology and is available in the range of small-scale from 200 kW to large scale systems. Therefore, gasification provides opportunity of developing small-scale decentralised bioenergy systems for conversion of the forest and rice residues, which can be located near the source of the residues in the rural areas in Malawi that lack access to grid electricity and other modern forms of energy. However, societal acceptance, awareness of the bioenergy systems from end users' viewpoint and social structures in the rural community need to be investigated to gain insights of potential state limiting stages to sustainable production of primary forest and rice residues-based bioenergy. The German Solar Energy Society (DGS, 2005), have argued that gasification of woody biomass is one of the most efficient and environmentally benign way of thermic utilisation of biomass to generate electricity in small plants. Table 2 shows a qualitative comparison of direct combustion, pyrolysis and gasification conversion of biomass to electricity

Table 2.2: Qualitative comparison of direct combustion, pyrolysis and gasification systems for electricity generation

	Technology & scale (250 kW_E – 1500 kW_E)		
Parameter	Direct combustion	Pyrolysis	Gasification
Availability on market	Available	Available	Available
Maturity	proven and mature		proven and mature
Efficiency	low	high	high
GCOE	low	high	moderate
Practical application for rural energy supply	high	low	High
Requirement for feedstock pre-treatment	none	high	high

2.10 Benefits of bioenergy production from primary forest and rice residues

The use of primary forest and crop residues is considered to have multiple positive benefits to the environment and the forestry, energy and agriculture sectors. Table 2.3 provides a summary of the benefits of utilising the residues for bioenergy production. Hammar et al., (2015) carried out a time-dependent life cycle assessment (LCA) of collecting logging (primary forest) residues for bioenergy production in South Sweden using a single-stand perspective. They found that collecting logging residues for bioenergy would have positive environmental impact on temperature change (global warming) mitigation potential per energy unit.

Table 2.3: Advantages of utilising forest and crop residues for bioenergy production

To forest sector	To agriculture sector	To energy sector	On the environment
▪ Can reduce the potential risk of forest fires thereby improving the health of forest stand. ▪ Can be source of additional income to the forest industry/sector. ▪ Can reduce the burden of waste disposal. ▪ Can improve growth of residual forest in partial harvesting system. ▪ Can reduce materials that can be breeding environment for pests ▪ Can improve forest health by reducing habitat for pests and invasive species ▪ Can reduce expenditures on clearing sites for replanting. ▪ Can improve site productivity.	▪ Can reduce the potential risk of open fires in farms and processing plants. ▪ Can be source of additional income to the farmers. ▪ Can reduce the burden of waste disposal. ▪ Can reduce materials that can provide favourable breeding environment for crop pests and diseases	▪ Can contribute to meeting the renewable energy targets. ▪ Can increase access to modern forms of energy to communities and households lacking not connoted to the grid electricity. ▪ Can support transition from woodfuel as traditional biomass to modern energy.	▪ Can reduce methane gas emissions from biodegradation of the residues in the forest plantations, farms and processing plants ▪ Can reduce uncontrolled burning of the residues from open fires

Hytönen & Moilanen (2014) have suggested that about 32 to 66 of the residues generated in forest plantations that consist of smaller diameters, should be left in the harvested areas to reduce the risk of microbial carbon depletion in the soils in the plantations. According to Repo et al., (2015), primary forest residues that consist of smaller diameters decompose faster than those of large diameter thus, adding humus in the plantations. Therefore, methods for evaluation of collectable quantities of primary forest residues from a harvested site in forest plantations need to account for this proportion of the residues for forest site conditioning.

Selection of sustainability criteria

The competitiveness of bioenergy lies in its renewability when compared with fossil fuels besides its versatility of production, storage, deployment and application when energy is needed when compared with wind and solar (Buragohain et al., (2010); Sims, (2002)). Selection of the criteria to include or leave out depends on the model boundary. Renewability of bioenergy is dependent on human activities in production, harvesting and management systems of the biomass feedstock. While carbon and energy balance can easily be quantified (Buchholz et al., (2009)), other sustainability criteria such as local community participation or food vs. fuel cannot be measured by exiting tools such as life cycle assessment or life cycle inventory, used for assessing sustainability of bioenergy production. Table 2.4 shows some of the criteria used in assessment of sustainability of bioenergy systems.

Buchholz et al., (2009), have pointed that the measurement of social (human factor related) criteria of sustainability of bioenergy systems is often hotly debated while even their significance is disputed amongst experts. However, these criteria, and the causal and effects thereof, can be modelled and demonstrated qualitatively using the dynamic systems approach. In addition, resilience of the source of the residues hence the residues-based feedstock supply chains, against contextual changes in technology, policy and anthropogenic activities/practices along the residues-based bioenergy production value chains has not been addressed by existing the methods for assessing sustainability of residues-based bioenergy systems.

Table 2.4: Sustainability criteria (adapted from Buchholz et al., 2009 with minor modification)

	Attributes			
Criteria	Relevance	Practicality	importance	Reliability
Energy balance	√	√	√	√
Greenhouse gases balance	√	√	√	√
Participation of stakeholders	√	√	√	
Ecosystem protection	√	√	√	
Food security	√	√	√	√
Waste management	√	√	√	√
Economic viability	√	√	√	√
Use of chemicals and fertilizer	√	√	√	√
Employment generation	√	√	√	√
Property rights	√	√	√	
Cultural acceptability	√	√	√	√
Exotic species application	√	√	√	√
Social cohesion	√	√	√	√
Land alienation	√	√	√	
Standard of living	√	√	√	

System sizing and selection of conversion technology

The selection of scale of operation of bioenergy systems depend on the biomass that is available in an area (Buchholz, 2009; McKendry 2002b). Thus, the capacity of the conversion technology needs to be benchmarked with the annual production of the biomass feedstock in the local area. Small-scale decentralised modular bioenergy systems can offer flexibility of increasing the scale of operation if feedstock production increases over time. Therefore, processes that can promote or limit steady flow or increase in biomass feedstock production and supply to a conversion plant need to be understood

2.11 Chapter summary

Sustainability assessment of residues-based bioenergy system is a complex nonlinear problem involving interacting structures in the primary systems that generate the residues and the bioenergy system. The methods which have been used to assess long term availability of forest and crop residues for bioenergy production lack the capability of capturing the dynamics in the residues production and supply chains. The methods are linear and event oriented, and incapable of demonstrating the causal-effects relationships of the feedback structures inherent in complex system involving interconnected and interacting feedback structures. In addition, existing modelling approaches have the capability of dealing with single component analysis. The complexity of bioenergy production from primary forest and rice residues is exacerbated by the interactions between the bioenergy production plant and sectoral policies that govern the production processes of the residues. The interconnectedness of these systems and the interactions between the components of the bioenergy system and the sectoral policies can cause variations in the residues supply chains, bioenergy production and supply to end users.

A systems approach modelling techniques, based on system dynamics methodology for modelling complex systems with feedback structures and nonlinearities, is appropriate for assessment of sustainable production of residues-based bioenergy. Owing to lack of reliable data, standardised approach of reporting residues to product ratio (RPR) and variations in RPRs of the sawmilling equipment, onsite assessment of the management and harvesting systems in the forest plantations is essential. Onsite assessment of the systems can enable the modeller to collect relevant data and capture the structures and mental models (qualitative and quantitative) from the stakeholders that represent the real world system. Onsite assessment and characterisation of the primary forest and rice residues in forest plantations and in rice farms respectively, is essential to understand the dynamics in the supply chains of the bioresources and predominant characteristic of the residues that can be collected for bioenergy production.

A multi approach assessment of sustainable production of bioenergy that combines the conventional methods of RPR with stakeholders' analysis and qualitative and quantitative systems approach modelling of bioenergy production can provide insights of the state limiting processes and policies to long term availability of the residues for bioenergy production, and availability and reliability of the bioenergy systems. The method can complement the RPR or GIS methods in generating valuable information for decision making, process and policy innovations in residues-based bioenergy beyond assessment of the quantities and locating the sites for residues collection and optimum distances to the conversion plants.

Chapter 3: Materials and methods

3.1 Introduction

This chapter provides broad overview of the methods used in this research. Specific and detailed methods to addressing the objectives of the research work are covered in the journal articles published or submitted to journals for publication, which form parts of this dissertation from Chapters 6 to 8. The main focus of this work was modelling sustainability of bioenergy production from residues-based feedstocks using the systems approach techniques discussed in detail in literature review in Chapter 2. The tools and materials used for data collection were selected based on the type of data required in system dynamics modelling. The methods include quantitative and qualitative research methods and are presented in the subsequent sections of this chapter.

A combination of desk study, field survey and simulation methods have been used to achieve the study objectives. In addition, multiple approaches (Axinn & Pearce, 2006 p19), such as interviews, group discussions and onsite validation of residues yield from harvesting of one hectare of mature stand in the Viphya forest plantations in Malawi were used. Data on rice production was obtained from Malawi Government database for evaluation of annual production of rice residues production. A systems approach model for sustainable production of bioenergy (SAS-Biopro model) has been developed for each of the two streams of feedstocks using system dynamics modelling software: Structural Thinking, Experimental Learning Laboratory with Animation (STELLA) Architect and Vensim.

3.1.1 Research ethics clearance

Research ethics is an essential component of good research, especially when the research involves obtaining information (collecting data) from individuals or a group of people as participants, respondents or subjects in the research (Oliver, 2003 pp1-5). Research ethics aims at promoting, sense of dignity and worthiness of the participants, integrity of the researcher, the results and funding agencies, and benefits of the research results to end users and the society (Israel & Hay, 2006 p2; Oliver, 2003 pp4-5).

Sustainability-related research is strongly linked to social (human) factors besides scientific (technological), regulatory, ecological, and economic capitals (Ashby, 2016;

Komiyama & Takeuchi, 2006; Brundtland Report, 1987). In addition, bioenergy, forest management and agricultural (farming) systems consist of the human capital linked and interacting together with the natural and economic capitals to achieve specific set objectives (Ashby, 2016; Musango, 2012; Buchholz et al., 2007). These linkages entail that assessment of sustainable production of bioenergy involves interacting with human participants or respondents that can provide relevant data, which is representing the real world or physical systems under consideration. Accurate data collected from stakeholders in forestry, rice farming and bioenergy systems can provide insights of the structures, processes, policies and practices that can be enablers or disenablers (state limiting stages) to sustainability of residues-based bioenergy production.

In addition, involvement of energy end-users in planning for the development and implementation of renewable energy systems has been advocated as an essential component in development of sustainable renewable energy systems (Zalengera et al., 2015). The systems approach modelling methodology, presented in Figure 2.3, is an interactive process with stakeholders involved in the systems and the problem being investigated and the users of the results generated using the model (Musango 2012; Sterman, 2000; Senge, 1990; Forrester, 1968). Therefore, this research involved interaction with human participants and respondents in Malawi to collect data used for developing and populating the systems approach model for sustainable production of bioenergy (SAS-Biopro model).

Research ethics clearance was obtained from the Research Ethics Committee of Stellenbosch University in South Africa (Appendix A3.1) where this study was based and from the Research Ethics Committee of the National Commission for Science and Technology (NCST) in Malawi (Appendix A3.2) where the field survey was conducted for data collection. In addition, letters of permission to conduct interviews and group discussions for data collection data from stakeholders in the sectors interlinked in the processes of bioenergy production were obtained from Malawi Government Ministry of Agriculture Irrigation and Water Development (Appendix A3.3) and Departments of Energy Affairs (Appendix A3.4). Furthermore, a consent form (Appendix A3.5) for voluntary participation in the survey was presented to each participant in duplicate before the interview or group discussion. The form was endorsed by both the participant/respondent that accepted to voluntarily participate in the survey and the interviewer after which the participant retained one copy of the form.

3.2 Research approach and sources of data

Research methods are categorised as quantitative, qualitative and mixed methods (Creswell, 2014 p31; Axinn & Pearce, 2006). The nature of the research problem influences the choice of the research method for data collection (Hox & Boeije, 2005). According to (Axinn & Pearce, 2006 pp18-19), combining multiple methods in data collection provides the opportunity of using multiple sources of information from multiple approaches to elicit new insights into the cause and effect relationships of variables and/or mental models in the problem being analysed. Using multiple methods in data collection has the advantage of compensating the shortfalls of individual methods thereby improving the quality of the research (Axinn & Pearce, 2006 p19).

In addition, the main focus in systems thinking and system dynamics modelling, as observed in section 2.4 of this dissertation, is analysing real world complex nonlinear problems. The existing problem can be global, regional, national or site specific in an organisation/industry. Gerring, (2007); Yin, (2003) have observed that the choice of research strategy (experimental, survey, case study) is influenced by the type of research and the research questions being addressed. As presented in sections 1.5.2.1 and 1.5.2.2, this study analysed residues-based bioresources supply chains to generate data for populating a model for sustainable production of bioenergy in Malawi. Therefore, case study research and site specific survey was considered appropriate strategy to answer the research questions.

A combination of qualitative and quantitative methods was used in this work to collect data for eliciting the model structure and populating the model for simulation. As pointed out in Chapter 2 section 2.3, system dynamics modelling captures both qualitative and quantitative information about the system and the problem being analysed. Qualitative and quantitative data are needed for the development of the model structures so that the model mimics the real world system behaviour that is under consideration. For instance, the perceptions, motivation, interests of the stakeholders and the influence that these may have on sustainability of the residues-based bioenergy system, need to be understood, in order to develop relevant innovations that can promote resilience of the bioenergy production value chains. Consequently, using multiple methods for data collection for systems approach modelling was an appropriate approach to collection of data for development, populating and simulation of the SAS-Biopro model.

(i) Synopsis of quantitative and qualitative research methods

Approaches to research design are categorised as quantitative and qualitative method (Tracy, 2013 p4; Babbie, 2010 p231). Quantitative methods focus on numerical measurements where data is expressed numerically based on the notion that numerical data provide the strongest impression of evidence and accuracy (Vanderstoep & Johnston, 2009 p7; Sapsford & Jupp, 2006 p153). In contrast to quantitative approach, qualitative methods focus on examination and interpretation of observations that are non-numeric for the purpose of discovering underlying meanings and patterns of relationships (Vanderstoep & Johnston, 2009 p8). However, as observed by Vanderstoep & Johnston, (2009, pp7-8), each of the two approaches has advantages and disadvantage as shown in Table 3.1 and it has been argued that none is superior to the other. The research objectives and the type of data needed to achieve the objectives are critical factors considered when choosing the research method to use to collect relevant data (Vanderstoep & Johnston, 2009 p8).

Table 3.1: Comparison between quantitative and qualitative research methods (adapted from Vanderstoep & Johnston, 2009, p7)

Characteristic	Quantitative method	Qualitative method
Type of data	Variables are described numerically	Facts are described in a narrative fashion
Analysis	Descriptive and inferential statistics	Identification of major themes
Scope of inquiry	Specific questions or hypothesis	Broad thematic concerns
Primary advantage	Large sample, statistical validity, accurately reflects the population	Rich, in-depth, narrative description of sample
Primary disadvantage	Superficial understanding of participants' thoughts and feelings	Small sample, not generalisable to the population at large

Although quantitative and qualitative methods are applied separately in research design and implementation, the methods are not mutually exclusive. Zalengera, (2015 p40); Vanderstoep & Johnston, (2009 p8) have suggested employing a two-pronged approach of quantitative and qualitative methods in complementary to each other. Combining the two methods is particularly necessary in interdisciplinary research involving data, which can numerically be measured and narrative data sets that can provide insights of the quantitative data and vice versa. For instance, in system dynamics modelling methodology, which will be discussed in detail in subsequent sections, qualitative data provide insights to the fundamental system structures responsible for the dynamic behaviour of the system over time demonstrated by the simulation (quantitative) model. Equally, the simulation model reveals the pattern of behaviour of the system over time stemming from narrative (qualitative) information in policy statements or operational procedures or guidelines as a consequence of the way management converts the information into action (Sterman, 2000). Therefore, a combination of quantitative and qualitative methods was used for data collection to achieve the objectives of this study.

(ii) Sources of data

Sources of research data are broadly categorised as primary and secondary sources (Axinn & Pearce, 2006). Data collected from primary and secondary sources are likewise categorised as primary and secondary data respectively (Hox & Boeije, 2005). According to Hox & Boeije, (2005), primary data are data that are collected for the specific research problem at hand, using the procedures that fit the research problem best. Primary data can be collected through experiments, surveys, observations and performance records (Phillips & Phillips, 2008) or from a combination of these methods. The advantage of collecting primary data is that a researcher collects the data specific to the research problem under consideration, which in turn adds new data to the stock of existing knowledge (Hox & Boeije, 2005). However, primary data collection is time and financial resource intensive which may limit the sources and amount of data accessed and collected by the researcher, respectively.

Secondary data are data from the work of other researchers or institutions that conducted the original investigation or study, for reuse in other research work (Hox & Boeije, 2005). Secondary data are obtained from published journal articles, reports or archived data of other researchers (Phillips & Phillips, 2008; Hox & Boeije, 2005). Secondary data provides the opportunity of collecting large amount of data stored or archived at one place. In addition secondary data may be found in processed format, which provides opportunity of collecting data that have been screened and analysed by the original researchers and data collection may not be time and financial resource intensive when compared with collection of primary data (Axinn & Pearce, 2006 p32). Secondary data may have the disadvantage of lack of guarantee of validity and accuracy, which depend on the methods and tools for data collection and analysis used by the original researchers, and may not be found in a format that is compatible to the research problem (Axinn & Pearce, 2006 p32). However, secondary data are useful when historical inferences are needed, time and financial resources to collect primary data are limited and when future trends are needed but can only be drawn adequately from a combination of primary and secondary data sets. Both primary and secondary data were collected and used in this study. The data sets were collected from literature, participants in a survey in Malawi and from onsite material balance in Viphya forest plantations using the methods and tools discussed in the subsequent sections.

3.3 Data collection

Data used in this dissertation were collected from desk study and a field survey conducted in Malawi between January and April 2015. Sources of data in the survey were identified and selected based on the type of data needed to achieve the study objectives, the sectors of economy or sections of the sectors that generate or store the data, and groups of stakeholders interconnected and interacting in the bioenergy production value chain. Table 3.2 shows the guiding information to the data needed, the type and sources of data identified for collection in the survey for the forest and rice residues value chains.

A combination of face to face interviews, focus group discussion and onsite validation of material balance on harvesting of mature forest stand were used to collect data for development and simulation of the SAS-Biopro model.

3.3.1 Tools for data collection: Structured and unstructured questionnaires

Questionnaires are instruments, which are specifically designed for collecting information useful for analysis (Babbie, (2010 p255). According to Babbie, (2010 p256; Phillips & Phillips, 2008 p1), a questionnaire consists of questions designed to solicit information from participants in field research, surveys, experiments and other modes of observations.

A questionnaire can be designed as highly structured or less structured. In a highly structured questionnaire, an interviewer is restricted to ask the questions as prescribed in the questionnaire and responses are categorised according to the categories prearranged by the research designer (Sapsford & Jupp, 2006 p95). In addition, respondents are restricted to select the answers to the questions from a list of answers against the questions (Babbie, 2010 p256). As observed by (Tracy, 2013 p139; Babbie, 2010 p256; Sapsford & Jupp, 2006 p95), highly structured questionnaires provide greater uniformity of responses and are easy to process than unstructured or semi structured questionnaires.

Structured questionnaires are effective for collecting data However, structured questionnaires lack flexibility and depth, discourage the interviewer from probing further than the scripted questions and answers (Tracy, 2013 p139). As a result, structured questionnaires may not capture the underlying structures of the problem known to the respondents but might have been overlooked by the research designers when preparing the questions and the list of answers (Sapsford & Jupp, 2006 p95). This implies that the underlying feedback structures in a complex dynamic system may not adequately be captured if only structured questionnaires are used for data collection for populating and simulation of systems approach models. Feedback structures, which may not be captured by structured questionnaires, can be the disenablers to sustainability of residues-based bioenergy systems.

Table 3.2: Data collection and the stakeholders engaged in the forest and rice residues value chains.

Primary forest residues value chain			Rice residues value chain		
Data for collection	Type	Source	Data for collection	Type	Source
Plantations management system	Primary	Regional Forest Office, and Viphya Plantations Management	Rice production in Karonga (2004 – 2014)	Secondary	Ministry of Agriculture.
Harvesting system	Primary	Plantations Management	Land cultivated for rice (2004 – 2014)	Secondary	Ministry of Agriculture.
Harvesting (2001 – 2014)	Secondary	Plantations Management	Rice marketing and sales	Primary	Rice cooperatives and rice farmers and
Sawyers population and productivity	Primary	Plantations Management and sawyers	Rice residues production	Primary and secondary	Rice cooperatives and rice farmers and
Harvesting technologies	Primary	Plantations Management and sawyers	Residues postharvest management	Primary	Rice cooperatives and rice farmers and
Timber and residues throughput	Primary and secondary	Plantations Management and sawyers	Productivity of rice farms	Primary and secondary	Rice cooperatives and rice farmers and
Residues postharvest management	Primary	Plantations Management, sawyers, timber & forest residues merchants	Rice residues competing uses	Primary	Rice farmers. KRADD
Residues for competing uses	Primary	Sawyers, transporters, timber & forest residues merchants	Rice cultivation water requirement	Primary secondary	Rice farmers and literature
Materials input	Primary	Sawyers and transporters			

Phillips & Phillips, (2008 p2) have asserted that semi structured or unstructured questionnaires stimulate a discussion between interviewer and respondent(s), thereby providing the opportunity to respondent(s) to provide their own answers to the questions. Equally, unstructured questionnaires provide opportunity to the interviewer to ask follow-up questions. As a result, data collection using semi structured questionnaires provides the opportunity to the interviewer to capture the underlying structures of a problem under consideration through engagement with the respondent in a discussion that leads to better understanding of the participants responses, opinion and beliefs (Phillips & Phillips, 2008 p2). However, Babbie, (2010 p256) has pointed out that data collected using unstructured questionnaires are more complex to analyse when compared to structured questionnaires. The data captured using unstructured questionnaires are qualitative and cannot be used to draw inferences of the entire population where the respondents were sampled from (Babbie, 2010 p256).

It can be observed that each of the two types of questionnaires has advantages and disadvantages. Similar to research methods, the choice of the format of questionnaire depends on the objectives of the study, type of data needed to achieve study objectives and the hypothesis being tested by the study (Babbie, 2010 p256; Sapsford & Jupp, 2006 p95). For this reason, structured and semi structured questionnaires were used for data collection in this study. Structured questionnaires were used for collection of quantitative data while semi structured questionnaires were used for collecting qualitative data from policy makers in forestry, energy and agriculture.

3.3.2 Desk study

Desk study covered searching for literature using titles of articles, key words, authors' names and key technical terminologies on library search engines and citation databases such as Scopus, Science Direct, Research gate, Google Scholar and Academia.edu for the purpose of literature review, development and simulation of SAS-Biopro model. In addition, secondary data, which have been cited in this dissertation, including the heating values of forest residues, efficiencies of biomass conversion technologies and carbon emissions conversion factors, were obtained from desk study.

3.3.3 Field survey

Data on forest and rice residues production, post harvest management of the residues and rural community energy needs were collected from two case study areas in northern Malawi: from Viphya forest plantations for the forest residues value chain and from rice farms in Karonga district for the rice residues value chain, respectively. Participants in the survey were drawn from eight categories of stakeholders in the forest, energy, agriculture and, transport sectors. The eight categories of stakeholders were selectively identified to participate in the survey based on position, profession, resource ownership and involvement in forestry and rice residues value chains, and in energy regulations and policy. Table 3.3 shows the categories of stakeholders identified and selected in the study.

Structured questionnaires with closed ended questions (Appendices A4.2 and A4.3) were used in interviews and group discussions with Vipha forest plantations management and regional forestry officers for data collection on forest management system, harvesting of mature stand, replanting of harvested sites, and residues production and postharvest management.

Table 3.3: Categories of stakeholders in field survey

Stakeholders
Policy makers (Energy, Forestry, Agriculture)
Sawyers
Rice farmers
Rural community households
Transporters
Traditional leaders
Civil Society Organisations
Merchants (timber and forest residues traders/sellers)

In addition, qualitative data were collected through group discussion and interviews methods, using unstructured questionnaires (Appendices A4.1 to generate information from the stakeholders for eliciting the structures of the bioenergy system based on primary forest residues from Viphya forest plantations. The interview and group discussion methods provide the opportunity of engaging the participants in a research more deeply than closed structured questionnaires (Tracy, 2013 p132; Phillips & Phillips, 2008 p24). According to Tracy, (2013 p132), interviews provide opportunity to respondents to explain subjectively real life experiences and viewpoints of the problem or system under consideration.

Phillips & Phillips, (2008 p24) have asserted that unstructured interviews for data collection provide opportunity for the researcher to ask follow up questions to participants, which may lead to revealing essential data needed to achieve the research objectives. Therefore, the unstructured interviews and focus group discussion methods for data collection for systems approach modelling of sustainable production of bioenergy have the potential of revealing the underlying structures causing the dynamic performance of the system, which in turn can be used for developing the qualitative (causal loop diagrams) and the simulation model of the primary forest residues-based bioenergy system.

3.3.3.1 Onsite validation of primary forest residues production in Viphya forest plantations

The data sets on harvesting of mature stand, timber and primary forest residues throughput per hectare per sawmilling technology, collected from Viphya forest plantations management, were validated through real time onsite assessment of harvesting of mature stand and sawmilling of logs into timber with a sawyer in the process of timber production on one hectare of the plantations. It was assumed that the biomass in a mature stand of *Pinus kesiya* and *Pinus patula* species above maturity age of 25 years was homogeneous. Forest management and harvesting systems practiced in the Viphya plantations are presented in detail in Chapter four of this dissertation.

Limitations: Reluctance of sawyers to participate in the study

Obtaining the sawyers' consent to participate in onsite assessment of harvesting of mature stand and timber production on their operating sites, and to study the processes on their equipment in Viphya plantations, was the main challenge faced with this method of data collection. Therefore, this assessment was limited to one mobile semi automatic Wood-Mizer LT20 plant, which the sawyer used for harvesting and sawmilling the logs on one hectare of mature stand.

3.3.3.2 Assessment of harvesting of mature stand for timber and primary forest residues production

To minimise disruption on the sawyer's operations in the timber production processes, the assessment was conducted on the logs which the sawyer prepared for processing into standard timber of 5.49 m long, 0.15 m wide and 0.051 m thick. From a mature stand of 1320 pine trees (1 hectare), the sawyer felled 154 trees using chain saws. Using the standard Table for Determining Minimum Returned Sample given in Appendix A5 (Bartlett et al., 2001) for continuous data with margin of error ME = 0.03, significance level $\alpha = 0.05$ (degree of confidence of 0.95), the minimum sample size from a stand of 1320 trees would have been 110 trees. However, all the logs from 154 trees that the sawyer had felled for timber production were used as a sample. Each tree was cut into a standard log of 5.49 metres long for sawing into timber using semi automatic Wood Mizer LT20, mobile sawmilling equipment. Three measurements of diameters were taken: at the base, middle and the tip of each log using a measuring tape. The methodology for evaluation of the amount and bioenergy potential of the residues generated in the Viphya forest plantations is presented in the manuscript submitted to the Journal of Energy for Sustainable Development, which is Chapter 6 of this dissertation.

3.3.3.3 Assessment of rice residues production in rice farms

Data on rice residues production in the rice farms in Karonga district were evaluated from a 10-year (2004 – 2014) statistical data of rice production collected from Ministry of Agriculture, Irrigation and Water Development in Malawi. The amount of residues produced in the rice farms per annum was estimated using residues to product ratio (RPR) from literature. The methodology for estimation of the residues and the bioenergy potential is provided in the manuscript that has been published in Renewable and Sustainable Review Journal with an Impact Factor of 8.05, which is in Chapter 8 of this dissertation.

3.3.3.4 Community Energy Situation Analysis (CESA)

Community situation analysis is a process of collecting vital information about a community's needs, asserts, investment and potential opportunities (resources, skills and knowledge) that can be harnessed to improve the existing condition (undesirable situation) and the livelihood of households in the community (Singletary, unpublished). Bhutto et al., (2011) have pointed out the lack of access to modern energy as one of the limiting factors to socio-economic development in developing countries, particularly in rural areas. Targeted supply of bioenergy from residues to rural communities where these bioresources are produced can promote participation of rural communities in the bioenergy value chain. As highlighted in section 2.8 in Chapter 2, the energy needs of end users of bioenergy is an essential factor for determining options of conversion process and technology of bioresources (McKendry, 2002b). Thus, the energy needs of the communities in areas where residues are produced need to be understood.

A community energy situation analysis (CESA) was carried out in two communities in Malawi. The purpose of CESA was to identify the energy needs and energy demand in the communities, where forest and rice residues are produced, and therefore, the selection of appropriate conversion process and technology for converting the residues to bioenergy that can meet the energy needs of the households, The energy needs and energy demand of two rural households were in a field survey conducted in the Viphya forest plantations and in the rice farms in Karonga district.

The hierarchy of energy needs of households in the rural communities was obtained in the survey. Data on energy consumption, energy sources used to meet the current energy needs, and priorities for future energy utilisation were collected using structured questionnaire (Appendix A4.2) adapted with permission from Zalengera, (2015). Questionnaires were administered to the heads of households in one rural community at Elamulen in the peripheral of the Viphya forest plantations in Mzimba district, for the forest residues and one community around Hara Rice scheme in Karonga district. Elamuleni community was identified through the district commissioner of Mzimba district while as participants at Hara rice scheme were identified through management of Hara Rice Producers and Marketing Cooperative Society.

A sample of 84 households, selected from a population of 462 households using simple random method from registers of village-heads, was interviewed at Elamuleni rural community. Table 3.4 presents the villages where the survey was conducted, population and the sample size for each village. A sample of 62 households purposefully selected by management of Hara Rice Producers and Marketing Cooperative Society was interviewed at Hara rice scheme. The survey was administered with the help of five research assistants.

Table 3.4: Minimum sample for data collection at Elamuleni rural community

Village	Population	Sample size	Actual respondents
Chembezi	57	9	14
Jutu	62	9	11
Kapuma	52	8	9
Matula	60	9	10
Petulosi	49	7	8
Zubani	27	4	5
Meramela	92	14	16
Jembelamala	63	10	11
Total	462	70	84

The questionnaires were reviewed by the Stellenbosch University and NCST Research Ethics Committees, presented in section 3.1 of the thesis, for ethical language. The questionnaires were administered in English and Tumbuka Languages to enhance fair understanding of the questions by the respondents. Research assistants were briefed for two hours on the processes of administering the questionnaires to respondents and capturing the data. Questionnaires administered each day were checked on daily basis for consistency of capturing the data from respondents.

3.4 Model development and simulation

The dynamic systems approach modelling methodology follows a preset procedure presented in Figure 2. 3. Owing to the differences in the forest management and rice farming systems that generate the forest and rice requires two model structures were developed using the same procedure. The model frameworks, boundaries variables and equations are presented in Chapter 4 and simulation results are presented in Chapter 5. In addition, detailed and specific materials and methods, which have been used to achieve the research objectives, have been presented in the manuscripts that form Chapter 6, Chapter 7 and Chapter 8 of this dissertation.

3.5 Chapter summary

An outline of the methodology, combining qualitative and quantitative research methods and system dynamics modelling methodology used in this research has been presented in this chapter. The chapter provides background information of the detailed materials and methods used to achieve the research objective, which have been presented in the article(s) published in peer reviewed journal(s) and those submitted for publication as outputs of this work. Although, approached from a case study point of view of assessing sustainable production of primary forest and rice residues-based bioenergy, the methodology can be used to assess sustainability of any residues-based bioenergy system.

Chapter 4: Systems approach model for sustainable production of residues-based bioenergy (SAS-Biopro model) development process

4.1 Introduction

The main objective of this study was to develop a model for sustainable production of bioenergy in Malawi. As highlighted in Chapter 3 section 3.4, a SAS-Biopro model framework has been developed for the primary forest and the rice residues supply chains. This chapter presents the model development process. Model equations of the variables considered in the modelling process, in relation to the purpose of the SAS-Biopro model were developed and have been presented in subsequent sections.

4.2 Model boundary

A systems approach model is considered to be valid and useful when it captures and represents the internally generated feedback structures of a problem being modelled, demonstrates the real pattern of performance over time of the system in which the problem exists, and gives insights that lead to formulation of effective policies to solve the problem (Barlas, 1996; Forrester & Senge 1979). In addition, formulation of the model and selection of the variables that can be included or excluded in the model building process is guided by the purpose of the model (Musango, 2012; Forrester & Senge 1979). As pointed out in section 1.8 in Chapter 1, the purpose of the SAS-Biopro model is to assess sustainability of primary forest and rice residues-based bioenergy value chains in Viphya forest plantations and in rice farms in Karonga district, respectively.

Specifically, the model demonstrates the effects of the interaction between structures in primary forest and rice residues-based bioenergy production emanating from forest management for timber production in Viphya forest plantations and rice production in the rice farms. The model boundaries were selected by paying particular attention to structures in the Viphya forest plantations management and rice farming systems that generate the residues, in order to choose the variables to be included or excluded from the model. The SAS-Biopro model provides insights of technological, process and policy innovations needed to promote resilience of the forest plantations management, the rice farming and the bioenergy production systems over time, which is a critical indicator that is not captured by other modelling approaches.

4.2.1 Model boundary and framework for the primary forest residues value chain

The SAS-Biopro model boundary for the primary forest residues value chain was selected to capture the structures that have the potential to cause intermittent supply (variations) of primary forest residues for bioenergy production over time. The SAS-Biopro model framework for the primary forest residues value chain is presented in Figure 4.1. The model captures the feedback structures in plantations management that influence variations in mature forest stand as a result of harvesting of mature stand, delayed and partial replanting of the harvested areas and postharvest management of the residues.

Specifically, the SAS-Biopro model for the primary forest residues value chain demonstrates the sources of variations over time in the primary forest residues supply chain and gives insights of points of high leverage where process or policy innovations can lead to stability of primary forest residues flow from Viphya forest plantations to a biomass conversion plant. The model consists of the following sub models: (i) harvesting of mature stand sub model; (ii) replanting of harvested area sub model and (iii) primary forest residues utilisation sub model.

Formulation of the SAS-Biopro model for the primary forest residues value chain was based on the following assumptions:

(i) The above ground biomass (agb) in mature forest stands aged above the maturity time of 25 years of the predominant pine tree species in the plantations are homogeneous to the volume of the logs sampled in this study, given in Figure 4.2.

(ii) The semi-automatic AMEC (AMECCO, China) and Wood-Mizer (Wood-Mizer, LLC, USA) sawmilling technologies, which are predominantly used by the sawyers operating in the plantations, have equal time efficiency (the time taken to split equal volumes of logs into timber is the same).

(iii) Only material flows that are altered by the integration of bioenergy production into the forest plantations management system are considered in the model.

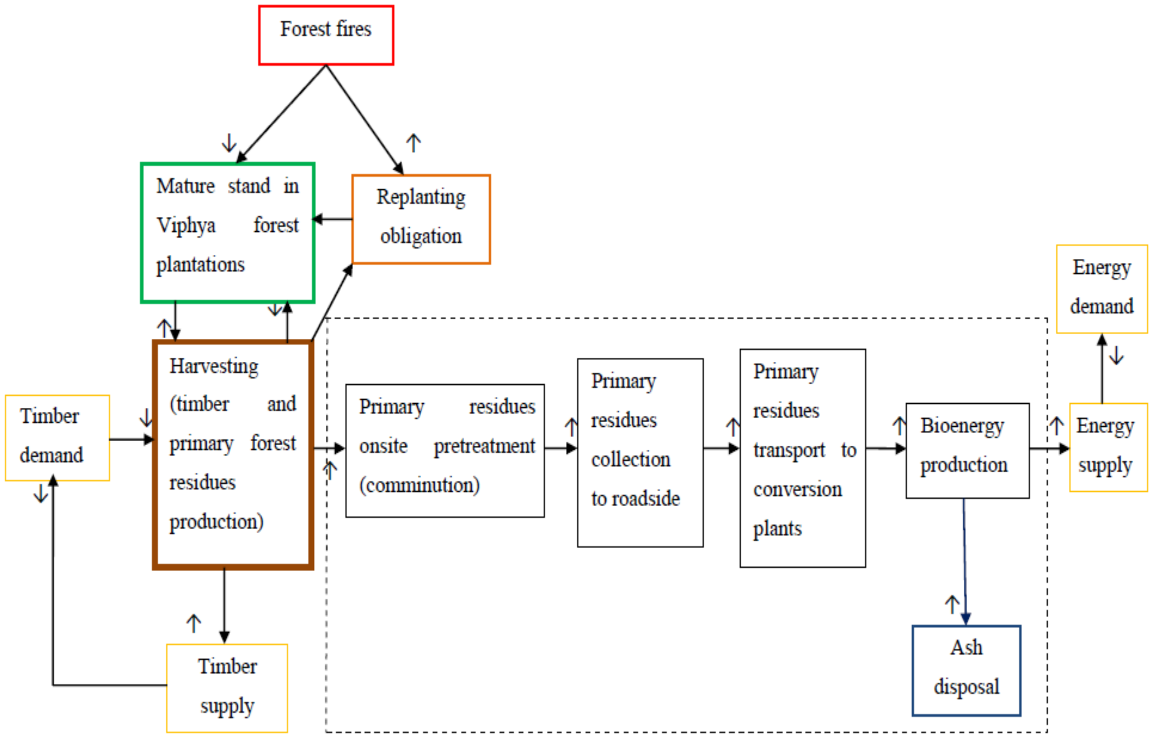

Figure 4.1: The modelling framework of sustainability of primary forest residues bioenergy production. Redrawn from Hammar et al., (2015) with slight modification

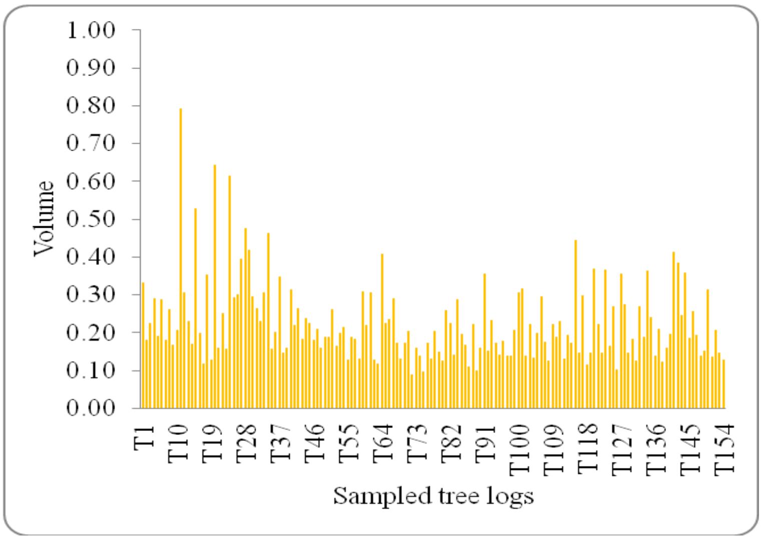

Figure 4. 2: The distribution of volume of sampled standard logs 5.49 m long from a mature stand in Viphya forest plantations in Malawi

4.2.2 Variables for the SAS-Biopro model for the forest residues value chain

The variables for the primary forest residues SAS-Biopro model are presented in Table 4.1. The variables capture internally generated feedback structures emanating from operational processes as well as external factors that have influence on mature stand, harvesting of mature stand and production of primary forest residues in Viphya forest plantations for bioenergy production. The variables represent the conceptual views captured in focus group discussion and from literature (Zalengera et al., 2014; Ngulube et al., 2014; Kafakoma & Mataya, 2009).

Table 4.1: Variables for the SAS-Biopro model for the primary forest residues value chain

Endogenous variables	Endogenous variables	Exogenous variables	Variables Left out
[3]Mature Stand	Sawyers on site	Timber demand	GDP
Harvesting	Timber production	Time to begin harvest	
Replanting	Residues production	Timber sales	
Area Removed from System	Primary forest residues	Energy demand	
Area remove from system	Timber profitability		
Harvested area	Bioenergy production		
[4]Young stand	Energy supply		
Maturing stand	Carbon sequestration		
Harvest productivity	Sequestered Carbon		
Replant or remove time	Total maturation time		
Immature stand	Replant fraction		
Impact of mature stand on harvesting	Replant remove flux		
Nominal harvest productivity	Transition time		
Sawyer staff size			

4.2.3 SAS-Biopro model equations for the primary forest residues value chain

The SAS-Biopro model for the primary forest residues value chain consists of four key stocks: the forest stand, the harvested area, forest residues and bioenergy. The forest stand sub model consist of stocks of mature stand that have reached maturity

[3] *Forest stand that have reached maturity age of 25 years and can be harvested*
[4] *forest stand planted in the harvested areas in the plantations which have not reached maturity age of 25 years*

age of 25 years, young stand replanted in the harvested areas and maturing stand. The harvesting sub model consist of harvested area, area left unplanted due to partial and delayed planting and non sequestered carbon. The residues and bioenergy sub model consist of the primary forest residues and residues for bioenergy stocks. Equations (4.1) to (4.24) have been developed and used in the stocks and flows simulation model of the forest residues value chain. Mature forest stands available in the plantations at any time t_2 are given by equation (4.1).

$$MS(t_2) = MS_{(t_1)} + \int_{t1}^{t2} (ms - mh) * dt \qquad (4.1)$$

Where: $MS(t_2)$ is the current stock of mature forest stand in ha at time t_2

$MS_{(t_1)}$ is the initial mature forest stand in ha at time t_1

ms is the maturing forest stand in ha/year

mh is the harvested mature forest stand in time dt in ha/year

dt is the time interval between $MS_{(t_1)}$ and $MS(t_2)$ in years

$MS_{(t_1)}$ = 33501 ha

The amount of mature forest stand harvested per year is a product of the number of sawyers operating in the plantations and the amount of mature forest stand each sawyer harvests per year (sawyer's productivity). Thus, harvesting of mature forest stand is given by equation (4.2).

$$HMS = S_N * SP \qquad (4.2)$$

Where: HMS is the mature forest stand harvested in ha/year

S_N is the number of sawyers operating in the plantations in sawyers

SP is the sawyers productivity (the average amount of mature forest stand harvested by each sawyer operating in the plantations) in ha/year

At the time of this study, the Government of Malawi (GoM) through the Department of Forestry (DoF) had licensed about 175 sawyers that harvested mature forest stand in the Viphya plantations. In addition, the values of sawyers productivity varied significantly between the value obtained from management report (6.23 ha/sawyer per year) and the value obtained from onsite inventory of mature stand (12 ha/sawyer per year).

Harvested sites in the plantations were not replanted immediately after harvesting. At the time of this study, only 40% of the area harvested between 2008 and 2014 had been replanted. Thus, the equation for replanting was developed to capture the flux that is replanted and that which is left out over time given by equation (4.3).

$$\mathrm{Rpl} = \mathrm{rr_f} * \mathrm{fr} \tag{4.3}$$

Where: Rpl is the area replanted in ha/year

fr is the fraction of harvested area of mature forest stand replanted = 0.4 (dimensionless)

$\mathrm{rr_f}$ is the replant removal flux in ha/year defined as the harvested area divided by the period between harvesting of mature stand and replanting of the harvested area, given by equation (4.4).

$$\mathrm{rrf} = \frac{\mathrm{HA}}{\mathrm{rrt}} \tag{4.4}$$

Where: $\mathrm{rr_f}$ is the replant removal flux in ha/year

HA is the harvested area in ha

rrt is the time taken to replant the harvested area in years which varies between 1and 25 years for an extreme condition of delay or to infinity (∞) for a very extreme condition of abandonment of the plantations.

The area harvested by the sawyers accumulated over time. The harvested area is evaluated using equation (4.5) in the model.

$$\mathrm{HA}(t_2) = \mathrm{HA}(t_1) + \int_{t_1}^{t_2} (\mathrm{HMS}) * dt \tag{4.5}$$

Where: $\mathrm{HA}(t_2)$ is the harvested area at time t_2 in ha

$\mathrm{HA}(t_1)$ is the initial harvested area at time t_1 in ha

HMS is the harvesting of mature forest stand in ha/year

dt is the change in time between initial and final stocks of the harvested area in years

$\mathrm{HA}(t_1) = 0$

After replanting 40% of the harvested area, 60% remains bare. The area that is left unplanted accumulates over time and is expressed as shown in equation (4.6) in the model.

$$HA_{ur}(t_2) = HA_{ur}(t_1) + \int_{t_1}^{t_2}(HMS - Rpl) * dt \qquad (4.6)$$

Where: $HA_{ur}(t_2)$is the harvested area of mature forest stand not replanted in the plantations at time t_2 in ha

$HA_{ur}(t_1)$is the initial area not replanted after harvesting mature forest stand in the plantations at time t_1 in ha

HMS is the harvesting of mature forest stand in ha/year

Rpl is the replanting of harvested area in ha/year

$HA_{ur}(t_1)$ = 0.

The accumulation of the area that is not replanted after harvesting the mature stand (Eq. 4.6) compromises the potential of carbon sequestration in the growing stocks in the plantations. The carbon that is not sequestered can increase the effects of global warming in the region. In addition, the declining amount of growing stocks of the forest stand can have effects on forest protection, biodiversity conservation and socio-economic benefits of the forest plantations (Brandt et al., 2016; Peng, 2000), besides the intermittent production and supply of the primary forest residues for bioenergy production.

The rate at which the harvested area is left out unplanted is evaluated using equation (4.7) in the model.

$$Rem = rrf * fr \qquad (4.7)$$

Where: Rem is rate at which the harvested area is left out unplanted in ha/year

rr_f is the removal replant flux in ha/year

$fr$is the fraction of harvested area of mature forest stand not replanted (unplanted fraction of the harvested area), which varies between 0 and 1 and is dimensionless.

The delay in maturing of replanted young forest stand, as a result of the maturity period of 25 years for the pine tree species planted in the Viphya plantations, has been accounted for by cascading the young forest stand replanted in the harvested area into five cohorts, A to E. It has been assumed that each cohort takes five years to transition from one cohort into the next cohort until they reach maturing age of 25 years. Therefore, the stocks of replanted young forest stand in the five cohorts are evaluated using equations (4.8) to (4.19) in the model.

$$\text{Stand A}(t_2) = \text{Stand A}(t_1) + \int_{t_1}^{t_2} (\text{Rpl} - \text{move AB}) * dt \qquad (4.8)$$

Where: $\text{Stand A}(t_2)$ is the stock in cohort A at time t_2 in ha

$\text{Stand A}(t_1)$ is the initial stand in cohort A at time t_1 in ha

Rpl is replanting of the harvested area in time dt in ha/year

move AB is the young stand transitioning from cohort A to cohort B in it time dt in ha/year

$\text{Stand A}(t_1) = 0$

$$\text{move AB} = \frac{\text{Stand A}}{\text{transition time}} \qquad (4.9)$$

$$\text{Stand B}(t_2) = \text{Stand B}(t_1) + \int_{t_1}^{t_2} (\text{Move AB} - \text{move BC}) * dt \qquad (4.10)$$

Where: $\text{Stand B}(t_2)$) is the stock in cohort B at time t_2 in ha

$\text{Stand B}(t_1)$ is the initial stand in cohort B at time t_1 in ha

Move AB is the young stand transitioning from cohort A to cohort B in time dt in ha/year

move BC is the young stand transitioning from cohort B to cohort C in time dt in ha/year

$\text{Stand B}(t_1) = 0$

$$\text{move BC} = \frac{\text{Stand B}}{\text{transition time}} \qquad (4.11)$$

$$\text{Stand C}(t_2) = \text{Stand C}(t_1) + \int_{t_1}^{t_2} (\text{Move BC} - \text{move CD}) * dt \qquad (4.12)$$

Where: $\text{Stand C}(t_2)$ is the stock in cohort C at time t_2 in ha

$\text{Stand C}(t_1)$ is the initial stand in cohort C at time t_1 in ha

Move BC is the young stand transitioning from cohort B to cohort C in time dt in ha/year

move CD is the young stand transitioning from cohort C to cohort D in time dt in ha/year

$\text{Stand C}(t_1) = 0$

$$\text{move CD} = \frac{\text{Stand C}}{\text{transition time}} \tag{4.13}$$

$$\text{Stand D}(t_2) = \text{Stand D}(t_1) + \int_{t_1}^{t_2} (\text{Move CD} - \text{move DE}) * \text{dt} \tag{4.14}$$

Where: $\text{Stand D}(t_2)$ is the stock in cohort D at time t_2 in ha

$\text{Stand D}(t_1)$ is the initial stand in cohort D at time t_1 in ha

Move CD is the young stand transitioning from cohort C to cohort D in time dt in ha/year

move DE is the young stand transitioning from cohort D to cohort E in time dt in ha/year

$\text{Stand D}(t_1) = 0$

$$\text{move DE} = \frac{\text{Stand D}}{\text{transition time}} \tag{4.15}$$

$$\text{Stand E}(t_2) = \text{Stand E}(t_1) + \int_{t_1}^{t_2} (\text{Move DE} - \text{maturing}) * \text{dt} \tag{4.16}$$

Where: $\text{tand E}(t_2)$ is the stock in cohort E at time t_2 in ha

$\text{Stand E}(t_1)$) is the initial stand in cohort E at time t_1 in ha

Move DE is the young stand transitioning from cohort D to cohort E in time dt in ha/year

Maturing is the young stand transitioning from cohort E to maturing cohort in time dt in ha/year

$\text{Stand E}(t_1) = 0$

$$\text{maturing} = \frac{\text{Stand E}}{\text{transition time}} \tag{4.17}$$

The transition time is given by equation (4.18)

$$\text{Transition time} = \frac{\text{Total maturity time}}{\text{number of immature stocks}} \tag{4.18}$$

Total immature stand (TIS) in the plantations is give by the sum of the five cohorts A to E which have not reached maturity age of 25 years and is given by equation (4.19)

$$\text{TIS} = \text{Stand A} + \text{Stand B} + \text{Stand C} + \text{Stand D} + \text{Stand E} \tag{4.19}$$

Harvesting of mature stand in the forest plantations depends on availability of mature stand. Two extreme conditions may exist in the extreme cases of poor management of the plantations: (i) when all the mature forest stand are depleted (no initial and current stock of mature stand to harvest) and (ii) all the forest stand are mature to harvest (initial and current stocks of mature forest stand are equal to 1). Therefore, to account for the impact of mature stand on harvesting, harvest productivity has been expressed as a function of the current and the initial stocks of mature stand in the plantations. Harvest productivity is given by equation (4.20) and the impact of mature stand on harvesting is evaluated using equation (4.21) in the model.

$$\text{HP} = \text{HP}_\text{N} * \text{IMSH} \tag{4.20}$$

Where: HP is the harvest productivity

HP_N is nominal harvesting productivity

IMSH is the impact of mature stand on harvesting

The impact of mature stand on harvesting is evaluated using a lookup or table function (Table 4.3) that defines the nonlinear relationships between mature stand and harvesting over time.

$$\text{IMSH} = \text{Graph}\left(\frac{\text{MS}}{\text{MS}_\text{in}}\right) \tag{4.21}$$

Where: IMSH is the impact of mature stand on harvesting (dimensionless)

MS is the current stock of mature stand in the plantations in ha

MS_in is the initial mature stand in the plantations in ha

Table 4.2: Lookup Table values for the graph

Mature Stand/INIT(Mature Stand)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Impact of mature stand on harvesting	0.0	0.07	0.17	0.44	0.62	0.74	0.85	0.92	0.95	0.98	1.0

Residues generated from harvesting of mature stand are evaluated using equation (4.22) in the model.

$$\mathrm{PFRP} = \mathrm{rgf} * \mathrm{HMS} \tag{4.22}$$

Where: PFRP is the annual production of primary forest residues in ton/year

rgf is the residues generation factor in ton/ha

HMS is the harvesting of mature stand in ha/yea

The amount of the primary forest residues that can be collected for bioenergy production is give by equation (4.23) that accounts for residues which are collected from the forest plantations by the stakeholders for other uses.

$$\mathrm{RB} = \mathrm{cfr} * \mathrm{PFRP} \tag{4.23}$$

Where: RB is the amount of primary forest resides that can actually be collected from the harvested sites for bioenergy production in ton/year

cfr is residues collection fraction (dimensionless)

PFRP is the annual production of primary forest residues in ton/yea

The stock of primary forest residues at the bioenergy conversion plant is evaluated by equation (4.24) in the model.

$$\mathrm{RB}(t_2) = \mathrm{RB}(t_1) + \int_{t_1}^{t_2} (\mathrm{cfr} * \mathrm{rgf} * \mathrm{HMS}) * dt \tag{4.24}$$

$$\mathrm{RB}(t_2) = \mathrm{RB}(t_1) + C_r \int_{t_1}^{t_2} \mathrm{HMS} * dt \tag{4.25}$$

Where: $\mathrm{RB}(t_2)$ is the amount of residues at time t_2 in tonnes in ha

$\mathrm{RB}(t_1)$ is the initial amount of residues at time t_1 in tonnes in ha

C_r is a constant evaluated as a product of the constants cfr (residues collection fraction) and rgf (residues generation fraction).

Equation (4.24) indicates that if the efficiency (rgf) of the logging and sawmilling technologies that are predominantly used for timber production in a plantation are known and a policy for regulating the amount of mature stand that can be harvested per year and the proportion of primary forest residues that can be collected from the forest plantations (cfr), then amount of primary forest residues that can be accumulated at a biomass conversion facility from a plantation can be reasonably estimated.

Results from simulation of the model have been presented in Chapter 5 and in a manuscript that forms Chapter 7 of this dissertation, which has been submitted to Biomass and Bioenergy Journal for publication.

4.3 Modelling sustainability of bioenergy production from rice residue

A SAS-Biopro model for the rice residues value chain was developed based on similar modelling methodology used for modelling the forest residues value chain presented in 4.2. The SAS-Biopro model for the rice residues value chain was developed for the purpose of gaining understanding of potential dynamics that may arise in a synergistically integrated bioenergy and rice production system in rice farms. In addition, the model gives insights of points of high leverage in a system that integrates rice and bioenergy production system, which require process and policy innovations to support the synergetic integration approach. The structure of the model and the results from simulation of the model are presented in a manuscript that forms Chapter 8 of this dissertation.

4.3.1 The rice residues value chain SAS-Biopro model boundary

As observed in 4.2 the boundary of the model is influenced by its purpose that influences the selection of variables that can be included or excluded in the development process of the model. Rice residues are obtained from rice production on arable land in rice farms. The residues are converted into bioenergy products in a conversion plant. The development and operation of the conversion of the residues to bioenergy involves investment, operational and maintenance costs. These costs influence the cost of energy generation and the price paid for the energy services by the energy end users. Therefore, the boundary of the model was selected to capture key variables from rice production to energy supply to end use processes in an integrated bioenergy and rice production system. Figure 4.3 shows the model framework and boundary. In this approach, bioenergy generated from the residues is supplied to the rice farms to support rice production.

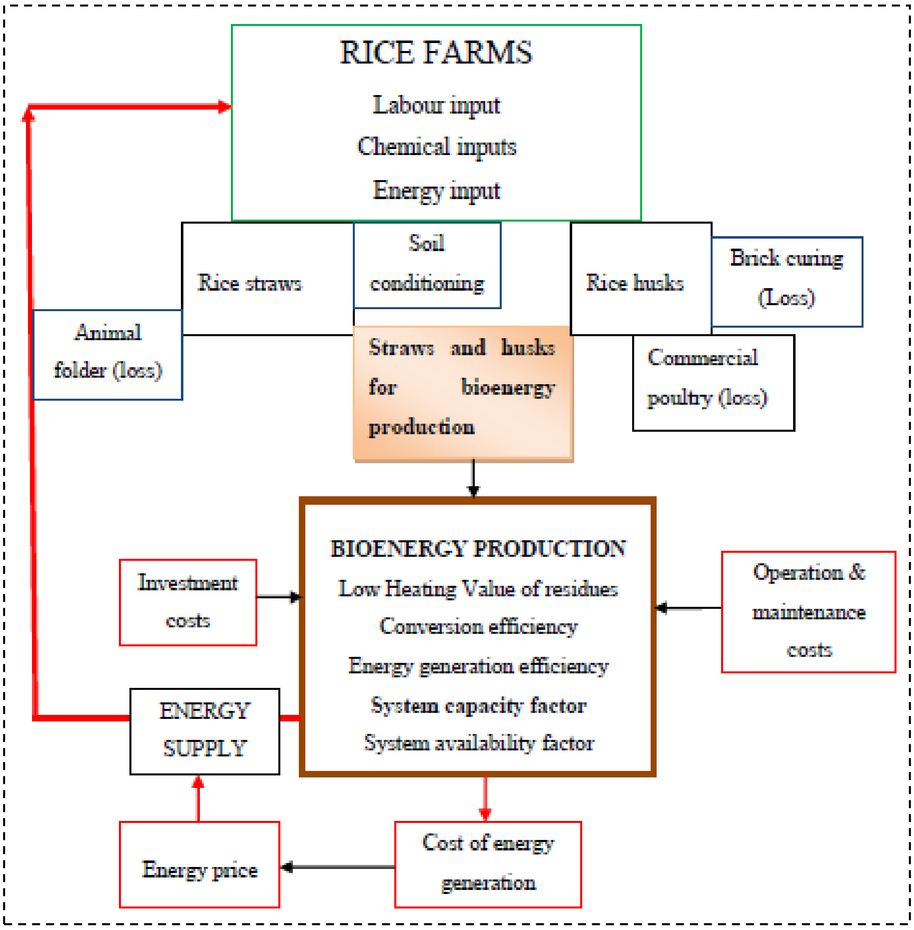

Figure 4.3: Modelling framework and boundary of the rice rsidues-based bioenergy system

4.3.2 Eliciting information from stakeholders in the rice residues bioenergy value chain

Qualitative data collected from sources and using approaches presented in Chapter 3 section 3.3 were thematically organised into key issues from the views raised by the stakeholders in the focus group discussions. The relationships between the thematic views from the stakeholders were established and developed into a cognitive map presented in Figure 4.4. As observed by Maani & Canana, (2007 p24), a cognitive map guides the modelling process by establishing the links of system structures based on information from the stakeholders' perception of the problem in the system.

The information in the cognitive map in Figure 4.4 was used for developing the dynamic hypothesis of the system. Rice straws that are used for animal fodder and rice husks used for curing bricks and for commercial poultry can influence variations in bioenergy production and supply to end use processes.

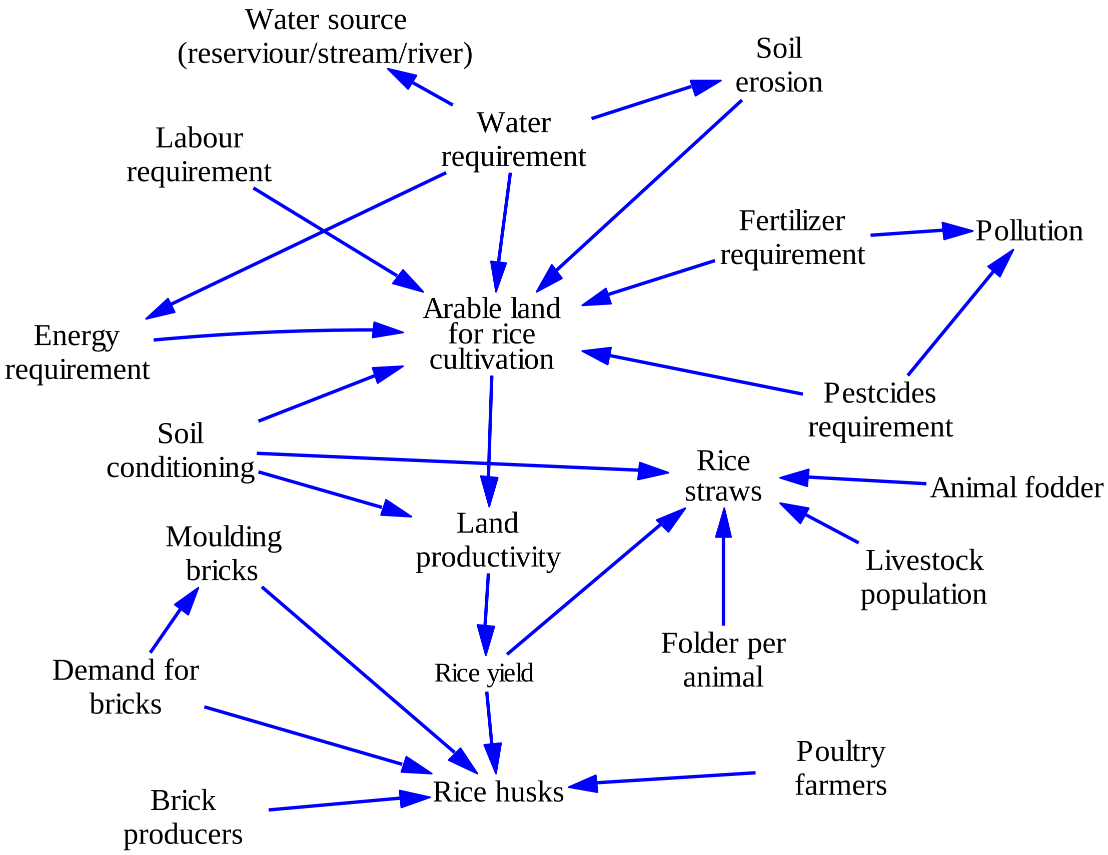

Figure 4.4: Cognitive map of the stakeholders views in the rice residues value chain

4.3.3 SAS-Biopro model variables for the rice residues bioenergy value chain

Variables of the SAS-Biopro model for the rice residues-based bioenergy system were elicited from the cognitive map in Figure 4.4. Table 4.3 presents the model variables. As observed by Sterman, (2000); Forrester, (1968), system dynamics modelling focuses on resources that form the structure of the problem in a system under consideration, the state (level or magnitude) of the resources, the rate at which the state of these resources are changing and the factors influencing the rate of change of the resources in the system. Consequently, the variables presented in Table 4.3 were identifies and selected to capture the state variables of the system.

Table 4.3: Variables for the rice residues bioenergy value chain

Endogenous variables	Exogenous variables	Variables left out
Irrigatable land	Arable land capacity	GDP
Arable land productivity	Food demand	Employment
Rice yield from wet planting	Demand for bricks	
Rice residues from wet planting	Poultry demand	
Rice residues losses	Animal fodder demand	
Rice production	Crop water requirement	
Residues to product ratio for straws		
Residues to product ratio for husks		
Residues supply to conversion plant		
Residues production from dry planting		
Residues production		
Loss fraction		
Feedstock drawing rate		
Conversion efficiency		
Gasifier conversion efficiency		
Bioenergy		
Energy supply		
Irrigation water		
Irrigation		
Water pumping energy requirement		
Irrigated rice yield		
Water supply to rice field		
Irrigated land productivity		
Water abstraction rate		
Irrigatable rice production		
Water pumping		
Water flow losses		

Assumptions

The 10-year historical data on rice production in the case study areas has been used in this study. The data is presented Table 8.4 in the manuscript in Chapter 8. The data shows that mean annual yields of 2.53 tonnes and 4.43 tonnes per hectare were obtained from rain-fed rice cultivation and gravity-fed irrigation of rice production, respectively. These values compare favourably with the values reported by Duku et al., (2016); Shen et al., (2004) that range between 1 and 4.4 tonne per hectare. Therefore, the mean rice yield values from the statistical rice yield data have been used in the model for evaluation of rice production.

4.3.4 Model equations for the SAS-Biopro model for the rice residues value chain

The SAS-Biopro model for the rice residues value chain consist of the following seven main stocks: rice yield from wet planting, rice residues from wet planting, bioenergy energy, irrigation water, irrigated land, rice yield from dry planting and rice residues from dry planting. Rice yield from wet planting in the model is the rainfall-based cultivated rice while as rice from dry panting is rice that is cultivated using irrigation water pumping. The state of the stocks and their rates of change have been evaluated using equations (4.26) to (4.49) which have been developed and used in the model for simulation.

Rice yield from wet planting is evaluated using equation (4.26) in the model.

$$RY_{WP}(t_2) = RY_{WP}(t_1) + \int_{t_1}^{t_2} (RP_{WP} - L_{WP}) * dt \qquad (4.26)$$

Where: $RY_{WP}(t_2)$ is rice yield from wet planting at time t_2 in ton

$RY_{WP}(t_1)$ is rice yield from wet planting at time t_1 in ton

RP_{WP} is rice production from wet planting in ton/year

L_{WP} is the loss in rice yield from wet planting in ton/year

Rice production wet planting has been evaluated as a product of the arable land used for rice production and land productivity (yield per unit of land per cropping season) and is given by equation (4.27).

$$RP_{WP} = Al_{WP} * lP_{WP} \qquad (4.27)$$

Where: $\mathrm{RP_{WP}}$ is rice production from wet planting in ton/year

$\mathrm{Al_{WP}}$ is the arable land for rice production for wet planting in ha

$\mathrm{lp_{WP}}$ is arable land productivity (yield per ha per year) from wet planting in ton/ha per year

Land productivity of 2.53 tonnes per hectare for wet planting and 4.43 tonnes per hectare for dry planting were evaluated from the annual rice yield statistics, which have been highlighted in the assumptions and in Table 8.4 in Chapter 8.

The losses in rice yield have been estimated using equation (4.28).

$$\mathrm{L_{WP}} = \mathrm{RY_{WP}} * \mathrm{lfr_{WP}} \tag{4.28}$$

Where: $\mathrm{L_{WP}}$ is the loss in rice yield from wet planting in ton/year

$\mathrm{RY_{WP}}$ is rice yield from wet planting at time in ton

$\mathrm{lfr_{WP}}$ is rice yield loss fraction from wet planting in dimensionless/year

Rice yield from wet planting that remains after accounting for the losses is used for evaluation of rice residues production that contributed to the initial stock of residues for bioenergy production in the SAS-Biopro model. The amount of rice that is actually available from wet planting after accounting for the losses is given by equation (4.29) and rice residues production is evaluated using equation (4.30) in the model.

$$\mathrm{RFC_{WP}} = (\mathrm{RY_{WP}} * (1 - \mathrm{lfr_{WP}})) \tag{4.29}$$

Where: $\mathrm{RFC_{WP}}$ is the amount of rice in ton/year from wet planting that is actually processed after accounting for the losses

$\mathrm{RY_{WP}}$ is the total rice yield from wet planting in ton

$1 - \mathrm{lfr_{WP}}$ is the fraction of the rice yield that can be processed and is dimensionless

$$\mathrm{RRP_{WP}} = (\mathrm{RFC_{WP}} * \mathrm{RPRs}) + (\mathrm{RFC_{WP}} * \mathrm{RPRh}) \tag{4.30}$$

Where: RRP_{WP} is rice residues production from wet planting in ton/year

RFC_{WP} is the amount of rice in ton/year from wet planting that is actually processed after accounting for the losses

$RPRs$ is residues to product ratio for rice straws (dimensionless)

$RPRh$ is residues to product ratio for rice husks (dimensionless)

The rice residues from wet planting are a stock variable that can either be accumulated or depleted, depending on the inflow (production) and outflows (losses and residues supplied to bioenergy conversion). Therefore, the amount of rice residues from wet planting is evaluated using equation (4.31) in the model.

$$RR_{WP}(t_2) = RR_{WP}(t_1) + \int_{t_1}^{t_2} (RRP_{WP} - RRL_{WP} - RSCP_{WP}) * dt \qquad (4.31)$$

Where: $RR_{WP}(t_2)$ are rice residues from wet planting at time t_2 in ton

$RR_{WP}(t_1)$ are initial rice residues from wet planting at time t_1 in ton

RRP_{WP} is rice residues production from wet planting of rice in ton/year

RRL_{WP} are rice residues losses from wet planting in ton/year

$RSCP_{WP}$ are residues for bioenergy production in ton/year

dt is the time interval between $RR_{WP}(t_1)$and $RR_{WP}(t_2)$in years.

$RR_{WP}(t_1) = 0$

The rice residues losses in equation (4.31) are estimated from straws that are used for animal folder and soil conditioning, rice husks used for burning bricks for construction and husks use for commercial poultry production. Equation (4.32) has been used for evaluating the rice residues losses in the model.

$$RRL_{WP} = (RR_{WP} * RSLfr) + (RR_{WP} * RHLfr) \qquad (4.32)$$

Where: RRL_{WP} are rice residues losses from wet planting in ton/year

RR_{WP} are rice residues from wet planting in ton

$RSLfr$ is rice straws loss fraction (dimensionless/year)

$RHLfr$ is rice husks loss fraction (dimensionless/year)

Rice residues from wet planting provide the initial annual feedstock requirement to a biomass conversion plant for bioenergy production for supplying to irrigation water pumping. Thus, residues supplied to a conversion plant are given by equation (4.33) and bioenergy production is evaluated using equation (4.34) in the model.

$$RSCP_{WP} = RR_{WP} * FDR \tag{4.33}$$

Where: $RSCP_{WP}$ is the amount of rice residues from wet planting supplied to a biomass conversion plant in ton/year.

RR_{WP} are rice residues from wet planting in ton

FDR is the feedstock drawing rate (the rate at which the residues are collected from the field (dimensionless per year)

$$Biopro = \eta_{GC} * \eta_{EE} * (RSCP_{WP} * LHV) \tag{4.34}$$

Where: $Biopro$ is bioenergy production in GWh/year

η_{GC} and η_{EE} are gasifier and spark ignition engine efficiencies used for conversion of the rice residues to electricity (dimensionless)

LHV is the low heating value of the residues in MJ/kg obtained from laboratory experiment and converted to GWh/year.

Bioenergy generated from the residues over time accumulates by means of bioenergy production as an inflow and is depleted by bioenergy supply to irrigation water pumping as an outflow and is given by equation (4.35).

$$BIOENERGY(t_2) = BIOENERGY(t_1) + \int_{t_1}^{t_2} (Biopro - BS) * dt \tag{4.35}$$

Where: $BIOENERGY(t_2)$ is bioenergy at time t_2 in GWh

$BIOENERGY(t_1)$ is initial bioenergy at time t_1 in GWh

$Biopro$ is bioenergy production in GWh/year

BS is bioenergy supplied to irrigation in GWh/year

is the time interval between $BIOENERGY(t_1)$ and $BIOENERGY(t_2)$

Initial $\mathrm{BIOENERGY}(t_1) = 0$

$$\mathrm{BS} = \mathrm{BIOENERGY} * \mathrm{SAF} \tag{4.36}$$

Where: BS is bioenergy supplied to irrigation water pumping in GWh/year
BIOENERGY is energy generated from the rice residues in GWh
SAF is the system availability factor (dimensionless/year)

Bioenergy is distributed to energy end use processes (the loads) from a node. Energy at the node is equal to bioenergy supplied from the conversion plant give by equation (4.37)

$$\text{Energy supply} = \text{Bioenergy supply} \tag{4.37}$$

The amount of water that can be pumped using bioenergy generated from the rice residues is evaluated as the energy supply from the residues divided by the energy requirement to pump unit volume of water and is give by equation (4.38).

$$\mathrm{WP} = \frac{\mathrm{ES}}{\mathrm{WPER}} \tag{4.38}$$

Where: WP is water pumping in m^3/year
ES is energy supply in GWh/year
WPER is water pumping energy requirement GWh/m^3

Water for irrigation accumulates by water pumping and is depleted by water flow losses and the amount of water abstracted for irrigation. Therefore, irrigation water is given by equation (4.39)

$$\mathrm{IW}(t_2) = \mathrm{IW}(t_1) + \int_{t_1}^{t_2} (\mathrm{WP} - \mathrm{Wfl} - \mathrm{WSRF}) \tag{4.39}$$

Where: $\mathrm{IW}(t_2)$ is water for irrigation at time t_2 in m^3
$\mathrm{IW}(t_1)$ is initial water for irrigation at time t_1 in m^3
WP is water pumping in m^3/yea

Wfl are water flow losses in m^3/year

$WSRF$ is water supplied to rice fields for irrigation in m^3/year

The water flow losses in equation (4.39) are evaluated using water flow loss factors in open channels. The values of the loss factors vary with the profile (shape) of the channel and materials used for construction (Chaudhry, 2008 pp55-80). Therefore water flow losses are given by equation (4.40)

$$Wfl = IW * flf \tag{4.40}$$

Where: Wfl are water flow losses in m^3/yea

IW is water for irrigation in m^3

flf is water loss factor in dimensionless/year

The quantity of water supplied to the rice field for irrigation is evaluated as a product of irrigation water and water abstraction rate and is evaluated using equation (4.41).

$$WSRF = IW * war \tag{4.41}$$

Where: $WSRF$ is water supplied to rice fields for irrigation in m^3/year

IW is water for irrigation in m^3

flf is the flow loss factor (dimensionless)

The amount of arable land that can be irrigated per year will depend on the amount of water pumped per year. However, the amount of water pumped per year will depend on energy supplied for water pumping. Therefore, capacity utilisation of the arable land for dry planting is nonlinear and is influenced by the water pumping capacity and the annual water requirement per unit of land for rice production. The relationship has been modelled using a table function presented in Table 4.4 where the effect of irrigation water pumping on land utilisation is a lookup function of water supply to rice field and rice crop water requirement

Table 4.4: Lookup function for the effect irrigation water pumping on arable land utilisation for dry planting of rice

Irrigation water pumping	Arable land utilisation
0	0
0.06	0.12
0.12	0.23
0.24	0.41
0.4	0.64
0.57	0.81
0.74	0.92
0.88	0.97
1	1
1.2	1

The arable land can be utilised for dry plant when there is adequate water pumped to the rice farms. The amount of arable land irrigated per year is expressed as the product of nominal capacity utilisation and total arable land used for rice production and is evaluated using equation (4.42). Nominal is evaluated as a fraction of irrigated land and the total arable land used for rice production.

$$\mathrm{ALI} = \mathrm{NLCU} * \mathrm{ALRP} \tag{4.42}$$

Where: ALI is arable land irrigated for dry planting of rice in ha/year

NLCU is nominal land capacity utilisation (dimensionless)

ALRP is the total arable land that is available for rice production in ha

Nominal land capacity utilisation is the nominal utilisation ratio of the arable land that can be irrigated annually with the supply of bioenergy to irrigation water pumping to the total land capacity and is dimensionless.

The land irrigated for rice production over time is given by equation (4.43).

$$IAL(t_2) = IAL(t_1) + \int_{t_1}^{t_2} ALI * dt \tag{4.43}$$

Where: $IAL(t_2)$ is the irrigated arable land in ha for rice production at time t_2;

$IAL(t_1)$ is the initial irrigated arable land in ha for rice production at time t_1;

ALI is the amount of arable land irrigated annually in ha/year;

dt is the time interval between t_1 and t_2.

$IAL(t_1) = 0$

Rice production from dry planting is evaluated as a product of Irrigated land in ha/year and Irrigated land productivity given by equation (4.44).

$$RP_{DP} = ALI * ILP_{DP} \tag{4.44}$$

Where: RP_{DP} is rice production from dry planting (irrigation) in ton/year;

ALI is the arable land irrigated in ha/year; and

ILP_{DP} is the irrigated land productivity in ton/ha.

The rice yield from dry planting as a stock increases with rice production as an inflow and decreases with the losses and rice supplied for consumption from dry planting. Therefore, rice yield is evaluated using equation (4.45) while as losses in rice production and the rice that would be available for processing and supplying to consumption after accounting for the losses are given by equations (4.46) and (4.47) respectively.

$$RY_{DP}(t_2) = RY_{DP}(t_1) + \int_{t_1}^{t_2} (RP_{DP} - RSC_{DP} - RPL_{DP}) * dt \tag{4.45}$$

Where: $RY_{DP}(t_2)$ is rice yield from dry planting in ton at time t_2

$RY_{DP}(t_1)$ is initial rice yield from dry planting in ton at time t_1

RP_{DP} is rice production from dry planting in to/year

RPL_{DP} are rice production losses from dry planting in ton/year

RSC_{DP} is the actual amount of rice in ton/year that can be accounted for and processed after the losses

dt is the time interval between t_1 and t_2

$RY_{DP}(t_1) = 0$

Rice production losses from dry planting are given by:

$$RPL_{DP} = RY_{DP} * lfr_{DP} \tag{4.46}$$

Where: $RY_{DP}$is rice yield from dry planting in ton

$RPL_{DP}$is the loss in rice

lfr_{DP} is the rice production loss fraction which is dimensionless/year

The amount of rice from dry planting processed and supplied to consumption:

$$RSC_{DP} = RY_{DP} * (1 - lfr_{DP}) \tag{4.47}$$

Where: RSC_{DP} is the amount of rice that can actually be accounted for and supplied to consumption in ton/year

RY_{DP} is the rice yield from dry planting in ton

$1 - lfr_{DP}$ is the fraction of rice yield that can actually be accounted for in the production value chain in dimensionless/year

The amount of rice residues generated from dry planting is the sum of the rice straws and husks from rice that can actually be accounted for in the rice production value chain and is given by equation (4.48).

$$RR_{DP}(t_2) = RR_{DP}(t_1) + \int_{t_1}^{t_2} (RRP_{DP} - RRL_{DP} - RRSC_{DP}) * dt \tag{4.48}$$

Where:$RR_{DP}(t_2)$ are rice residues from dry planting at time t_2 in ton

$RR_{DP}(t_1)$ are initial amount of rice residues from dry planting at time t_1 in ton

RRP_{DP} is rice residues production from dry planting of rice in ton/year

RRL_{DP} are rice residues losses from dry planting in ton/year

$RRSC_{DP}$ are residues from dry planting for bioenergy production in ton/year

dt is the time interval between $RR_{DP}(t_1)$and $RR_{DP}(t_2)$in years.

$RR_{DP}(t_1) = 0$

Similarly, rice residues generated from dry planting that can be collected for bioenergy production, after accounting for losses to other uses, are supplied to the bioenergy conversion plant for bioenergy production. The amount of rice residues from dry planting supplied to a biomass conversion plant is evaluated using equation (4.49) in the model.

$$RSCP_{DP} = RR_{DP} * FDR \qquad (3.49)$$

Where: $RSCP_{DP}$ is the amount of residues supplied to a conversion plant in ton/year

RR_{DP} is the amount of rice residues from dry planting of rice in tonnes

FDR is the feedstock drawing rate in dimensionless/year

4.4 Chapter summary

This chapter presented the model frameworks, model boundaries and equations that define the key stocks and flows of the SAS-Biopro models for the primary forest and the rice residues value chains. The model boundaries and equations accounted for key variables in primary systems that generated the residues. Only variables that had the potential of influencing variations in availability and supply of the residues and the dynamic performance of the systems over time were considered. The results from simulation the models are presented in Chapter 5, 7 and 8.

Chapter 5: Results

5.1 Introduction

Simulation results from the SAS-Biopro models of primary forest and rice residues-based bioenergy value chains showed that variations in the supply chains of the residues for bioenergy production emanate from forest plantations management and rice farming systems, respectively, and from postharvest management of the residues. Specifically, inadequate investment in the forest plantations management, logging and sawmilling technologies used for harvesting mature stands, harvesting systems and postharvest management operations of the residues in the forest influenced variability in stocks of the residues over time. The variations in mature stands that can be harvested for timber productions in the Viphya forest plantations influenced variations in primary forest residues and bioenergy production over time.

Simulation results of the SAS-Biopro model for scenarios, obtained by varying the harvesting rate, mortality fraction, and replanting rate per annum, showed that implementation of a threshold for harvesting mature stand (annual allowable cut) of 7 ha per sawyer per year, and increasing investment from 40% of the annual plantations management operational budget provided to plantations management, to 100% to improve silvicultural operations, reduce mortality fraction of replanted trees from 0.35 to < 0.1, reduce forest fire risks and incidences, and increase monitoring of the forest plantations, can promote steady availability of mature stand for timber and forest residues production that can be used for bioenergy production. Whole systems integration of bioenergy and timber production in forest plantations and synergetic integration of bioenergy and rice production in rice farms can promote development, deployment and operation of sustainable primary forest and rice residues-based bioenergy systems. In addition, whole systems and synergetic integration approaches can promote resilience and steady flow of the residues over a long time horizon.

5.2 [5]Annual production, availability and bioenergy potential of primary forest residues

Assessment of harvesting system of mature stand, logging sawmilling technologies, replanting of the harvested area and postharvest management of primary forest residues

[5] Detailed results of this section have been presented in manuscripts, which are Chapter 6 and 7 of this thesis.

on 33501 ha section of the Viphya forest plantations showed variations in mature stand simulated over a time horizon of 100 years. Figure 5.2 shows the variations in stocks of mature forest stand over the simulation time horizon. Variations in mature forest stand were influenced by over-exploitation of the mature stand for timber production, delayed replanting of harvested areas, high death (mortality) rate of replanted trees and underinvestment in plantations management. In addition, inefficient sawmilling technologies, which generated large quantities of residues, contributed to rapid depletion of mature stand, promoted variations in availability of mature forest stand overtime. The lack of harvesting plan contributed to unaccounted for harvesting of mature stand and unsynchronised harvesting and replanting in the plantations. As a result, mature forest stand in the 33 501 ha-section were depleted in 15 years before the maturity time of 25 years on the pine trees in the plantations (Fig. 5.2a).

5.2.1 Highlights of the findings in the forest residues value chain

Onsite inventory of primary forest residues production in the plantations showed that significant quantities of residues generated on harvested sites were underutilised and poorly managed after harvesting. About 65% of the residues were left on the harvested sites and burnt by forest fires during hot summers. The composition and proportion of primary forest residues produced per hectare have been presented in Figure 5.1. About 96% of the residues were barks and round logs from branches (Fig. 5.1a, 5.1c, and 5.1d). Residues production per hectare varied with sawmilling technology (Table 5.1). Residues generated per annum could be used to supply annual feedstock requirement of 16 gasifiers rated 750kW$_E$ which, cumulatively could supply 69.92 GWh$_E$ per annum. The investment in the system would pay back the investment in the 8th year. Soft systems (qualitative) modelling indicated that bioenergy systems utilizing primary forest residues in Malawi could be more sustainable if supplied to rural communities around the plantations. Rural communities as mobilisers of the residues for bioenergy production and energy end users would increase rural community participation in nurturing the plantations.

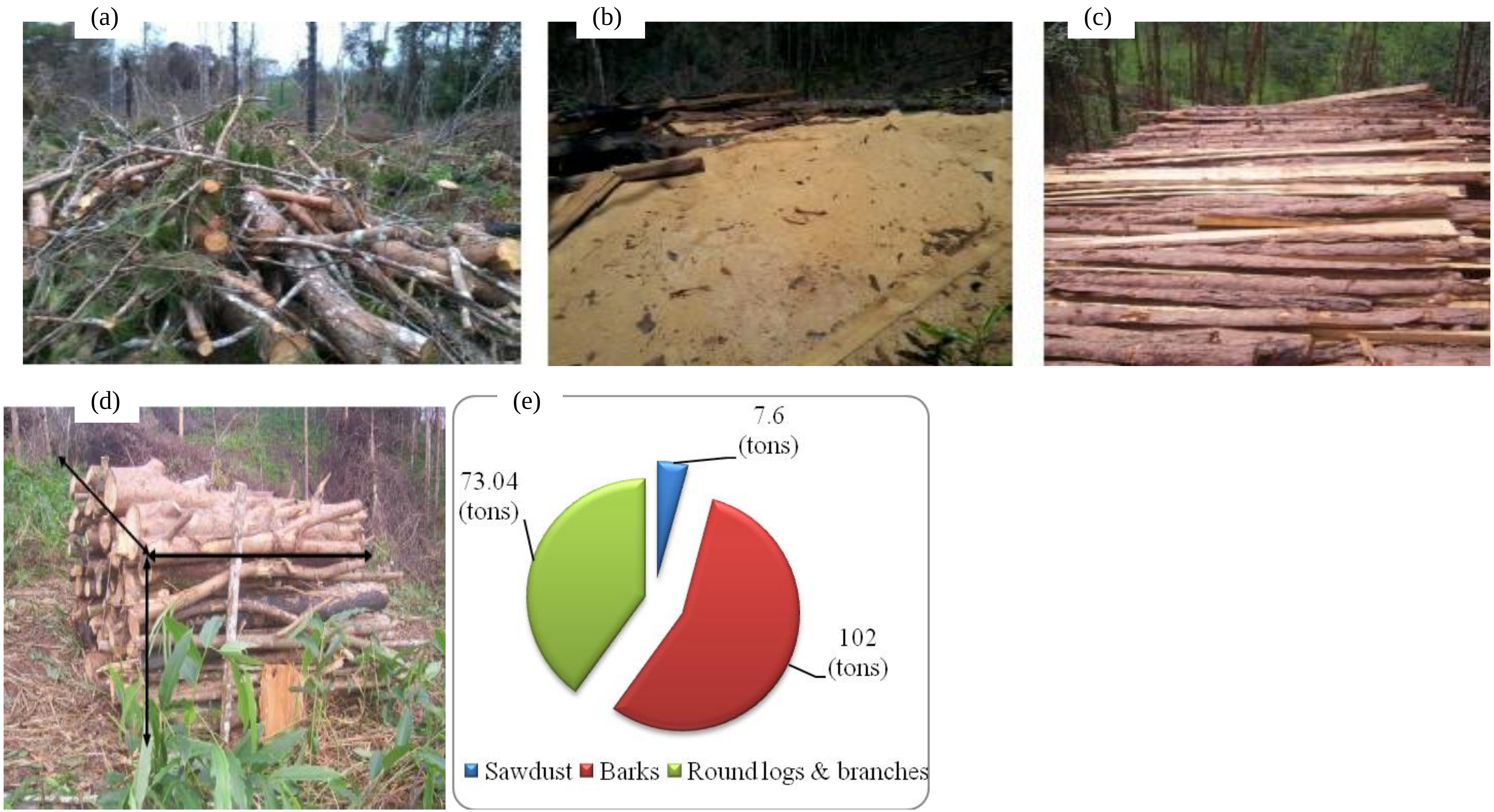

Figure 5.1: Primary forest residues generated from logging and sawmilling processes left on the harvest sites in Viphya forest plantations in Malawi: (a) rejected round logs and branches, (b) sawdust, (c) barks, (d) sample of piles used for assessing the amount of round logs and branches, (e) proportions of the residues evaluated onsite.

The clear cut mature forest stand harvesting system practiced in this section of the plantations requires intensive forest management of the plantations to promote steady availability of both timber and primary forest residues. However, only 40% of the area annually harvested between 2008 and 2014 was replanted by 2015. Lack of investment in plantations management also resulted in lack of capacity to control forest fires leading to loss of 35% of young stand replanted every year. Unsynchronised replanting also compromised carbon sequestration potential of the plantations. Thus, management and harvesting systems of the Viphya forest plantations do not promote sustainability of the plantations.

Table 5.1: Residues generation and associated bioenergy potential

Type	Source	Residues generation fraction (rgf)	Residues Yield (tons/ha)	Annual residues production (tons/year)	Bioenergy potential (PJ/year)
AMEC mills	Logging and Sawmilling	0.65	269	236720	3.6
Wood-Mizer mills	Logging and Sawmilling	0.45	178	39160	0.59
Aggregated annual production	Logging and Sawmilling of 1100 ha			275880	41. 4

5.2.1.1 [6]*Simulation results of the primary forest residues SAS-Biopro model*

The causal loop diagrams and the structures of SAS-Biopro model have been presented in the manuscript in Chapter 7. The SAS-Biopro model for the forest residues was simulated in forty five runs of five scenarios for a time horizon of 100 years from 2000 to 2100. The time horizon of 100 years represents four cycles of harvesting and replanting of the forest plantations. The runs and scenarios have been presented in Table 5.2 and Table 5.3, respectively.

[6] Detailed discussion of the results is also presented in the manuscript in Chapter 7, which has been submitted for publication in Biomass and Bioenergy Journal.

Table 5.2: Simulation runs for the SAS-Biopro model for forest residues value chain

Simulation	Harvesting rate (ha/year/sawyer)	Replanting rate (% of harvested area)	Death fraction (of replanted trees)	Sawyers population
Run 1	12	0	0.35	175
Run 2	12	40	0.35	175
Run 3	12	80	0.35	175
Run 4	12	100	0.35	175
Run 5	12	100	0.2	175
Run 6	12	100	0.1	175
Run 7	12	100	0	175
Run 8	7	100	0.1	175
Run 9	7	100	0.05	175
Run 10	7	100	0	175
Run 11	7	40	0.35	175
Run 12	6.23	40	0.35	175
Run 13	6.23	80	0.2	175
Run 14	6.23	100	0.1	175
Run 15	6.23	100	0	175
***What IF new species of trees with maturity time of 15 or 35 years are introduced*?**				
Run 16	12	0	0.35	175
Run 17	12	40	0.35	175
Run 18	12	80	0.35	175
Run 19	12	100	0.35	175
Run 20	12	100	0.2	175
Run 21	12	100	0.1	175
Run 22	12	100	0	175
Run 23	7	100	0.1	175
Run 24	7	100	0.05	175
Run 25	7	100	0	175
Run 26	7	40	0.35	175
Run 27	6.23	40	0.35	175
Run 28	6.23	80	0.2	175
Run 29	6.23	100	0.1	175
Run 30	6.23	100	0	175

Table 5.3: Scenarios for simulation of forest stand dynamics, primary forest residues and bioenergy production

Simulation run	**Scenario**
Run 2	Maintain the status quo of over exploitation of mature forest stands (12 ha per sawyer per annum) and low investment in forest plantations management that leads to high death rate of replanted trees, lack of capacity to monitor and control forest fires, and inadequate monitoring of sawyers activities in harvesting mature stand in the plantations. This is presented as Business As Usual (BAU) scenario.
Runs 3 to 7	Increase investment in plantations management to improve silvicultural operations, reduce forest fire risks and incidences and improve monitoring of the plantations. This scenario is presented as Improved Management Capacity (IMC).
Runs 8 to 11	Implement an optimum harvesting rate (annual allowable cut) of 7 ha of mature stand per sawyer per year and increase investment to reduce forest fire risks and incidences, improve silvicultural operations and monitoring of the plantations. This is referred to as annual allowable cut - Improved Management (AAC-IMC) scenario.
Run 12	Harvest below optimum at 6.23 ha of mature stand per sawyer per year and maintain status quo of low investment that lead to high death rate of replanted trees, lack of capacity to monitor and control forest fires, and inadequate monitoring of sawyers activities in harvesting mature stand in the plantations. This scenario is referred to as Below Optimum-Business As Usual (BO-BAU) scenario.
Runs 13 to 15:	Harvest below optimum at 6 ha of mature stand per sawyer per year and increase investment to reduce forest fire risks and incidences, improve silvicultural operations and monitoring of the plantations (Below Optimum Improved Management Capacity – BO-IMC) scenario. Sawyers improve timber annual throughput by means of utilising efficient technologies
Run 1	Extreme conditions of zero replanting of harvested areas. It implies abandonment of the plantations, which may not exist. Similarly, 100% survival rate of replanted trees is an ideal condition of tree survival.

A comparison of simulation results within and across the scenarios showed that the decrease in availability of mature stand for harvesting for timber production over time caused the decrease in production of primary forest residues and bioenergy over time. For instance, the prevailing situation in the Viphya forest plantations in Malawi, presented as business as usual (BAU) scenario in Run 2 in Figure 5.2(a) represents the case of over exploitation of mature stand at 12 ha per sawyer, partial replanting of 40% of the harvested area and death fraction of 0.35 of replanted trees per year. Simulation results of the BAU scenario showed the decrease in mature stand, immature stand, harvesting of mature stand, residues and bioenergy production over time as presented in Figure 5(a), 5(b) and 5(c). The BAU scenario indicated that significant quantities of primary forest residues were produced at the beginning of harvesting (Fig. 5b) when availability of mature forest stand also was high. However, the scale of a bioenergy production system that could be developed based on the primary forest residues generated in the initial stages of harvesting mature stand could be operated below full capacity over time owing to the decrease in residues production as mature stand decreased over time in the plantations.

The high mortality fraction (0.35) of young and growing stocks of trees in the Viphya forest plantations was as a result of the impact of inadequate investment in forest plantations management on plantations management capacity to nurture the plantations. The impact of investment on management capacity was modelled as an exponential decay of tree survival in the plantations. This is further discussed in the dynamic hypothesis of the forest residues-based bioenergy production value chain in Chapter 7.

Figure 5.3 shows a comparison of the stocks of mature and immature stand, primary forest residues and bioenergy production between the BAU (Run 2) and AAC-IMC scenarios (Run 8). The AAC-IMC scenario was determined by varying the harvesting and replanting rates and death (mortality) fraction of the replanted trees and growing forest stand from 12 ha per year per sawyer, 40% and 0.35 in BAU scenario to 7 ha per year per sawyer, 100% and 0.1 in the AAC-IMC scenario in the Viphya forest plantations. Mortality fraction and replanting rates were varied based on the assumption that increasing investment in the plantations management could improve silvicultural operations, increase replanting rate, and reduce forest fire risks and incidences thereby decreasing the mortality fraction of replanted trees.

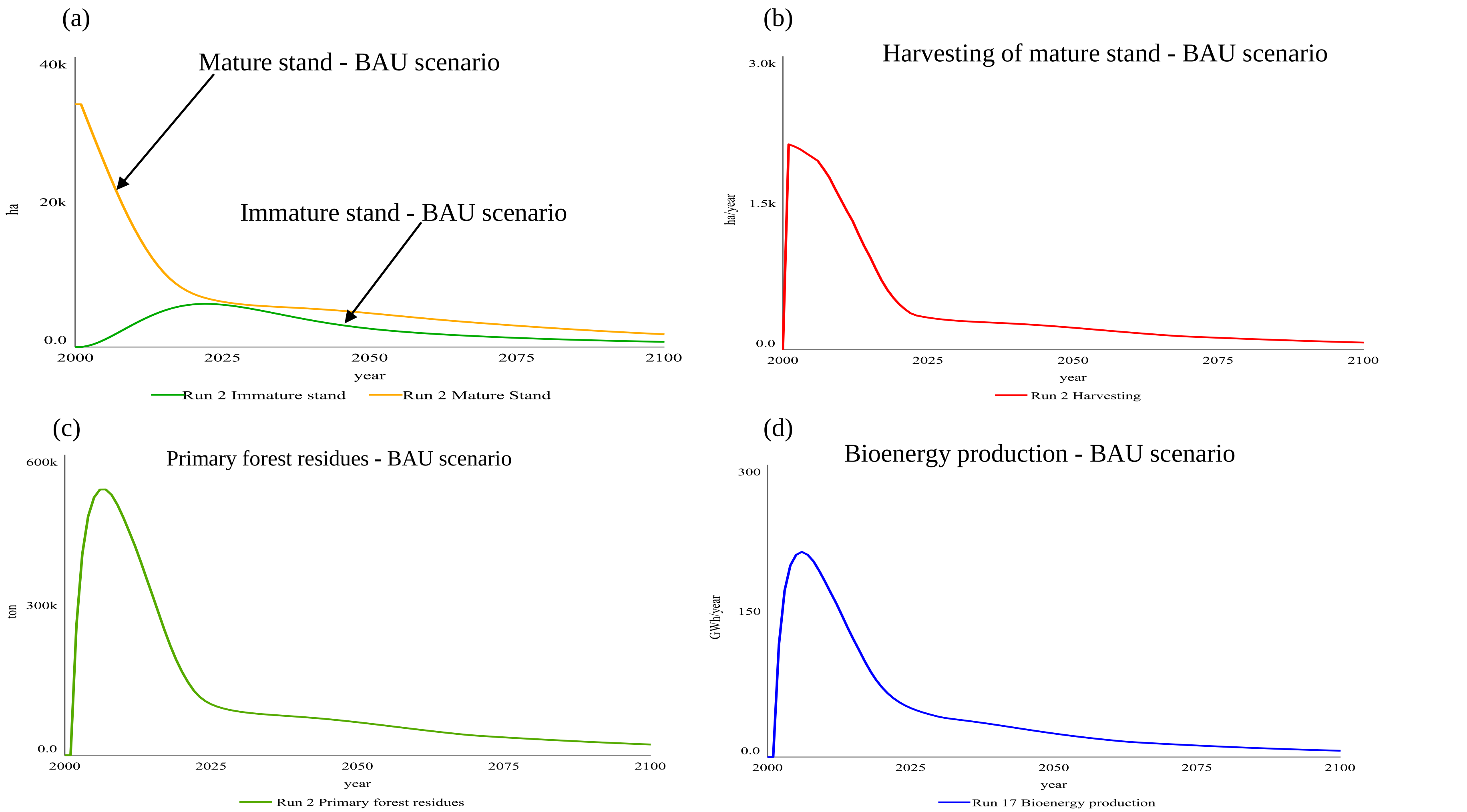

Figure 5.2: Stocks variations over time within the BAU scenario: (a) Decrease in stocks of mature and immature forest stands over time; (b) decrease in harvesting of mature forest stand for timber production over time; (c) decrease in primary forest residues production over time; (d) decrease in bioenergy production over time.

Simulation results of the model presented in Figure 5.3(a) show that the AAC-IMC scenario (run 8) promoted steady availability of both mature and immature forest stand over time. Stability in availability of mature stand, that could be harvested for timber production over time promoted stable flow of primary forest residues for bioenergy production as shown in Run 8 in Figures 5.3(b) and 5.3(c).

Results from the other scenarios in Table 5.3 have been presented in Figure 5.4. The improved management capacity (IMC) scenario was simulated by varying the replanting rate between 40% and 100% of the harvested area in Runs 3 and 4 while keeping the harvesting rate and the death fraction of replanted trees constant at 12 ha per sawyer per year and 0.35 respectively. The below optimum-business as usual (BO-BAU) scenario was simulated by varying the harvesting rate per sawyer per year while keeping the replanting rate and death fraction constant at 40% and 0.35 (Run 12). Below optimum – improved management capacity (BO-IMC) was simulated by varying the harvesting rate from 12 ha to 6.23 ha per sawyer per year, the death fraction from 0.35 to 0 and replanting rate of the harvested area from 40% to 100%.

Simulation results from the three scenarios presented in Figure 5.4 showed that the stocks of mature and immature stands, harvesting, primary forest residues and bioenergy production increased over time compared to BAU scenario (Run 2). However, the trend of declining stocks of mature and immature stands was observed in the IMC (Runs 3 to 7) and BO-BAU (Run 12) scenarios. Although simulation results of the BO-IMC scenario showed constant availability of mature stands for harvesting for timber production over time, the scenario promoted underutilization of the plantations when harvesting of mature stands, replanting of the harvested sites and maturity time of the predominant tree species in the plantations were synchronised compared to AAC-IMC scenario.

Effects of maturity time of trees on stocks of mature stand over time

The effects of replacing *Pinus patula* and *Pinus kesiya* tree species, which are predominant species planted in the Viphya forest plantations (Ngulube et al., 2014), with fast or slow maturing (25±10 years) species on long term steady availability of mature stands for timber and primary forest residues production were evaluated in the model by varying the total maturity time between 15 and 35 years. The simulation runs of the five scenarios were repeated from Run16 to Run 30 for maturity time of 15 years and Runs 31 to 45 for maturity time of 35 years. The simulation results showing mature forest stand dynamics for the BAU and AAC-IMC scenarios are presented in Figure 5.5.

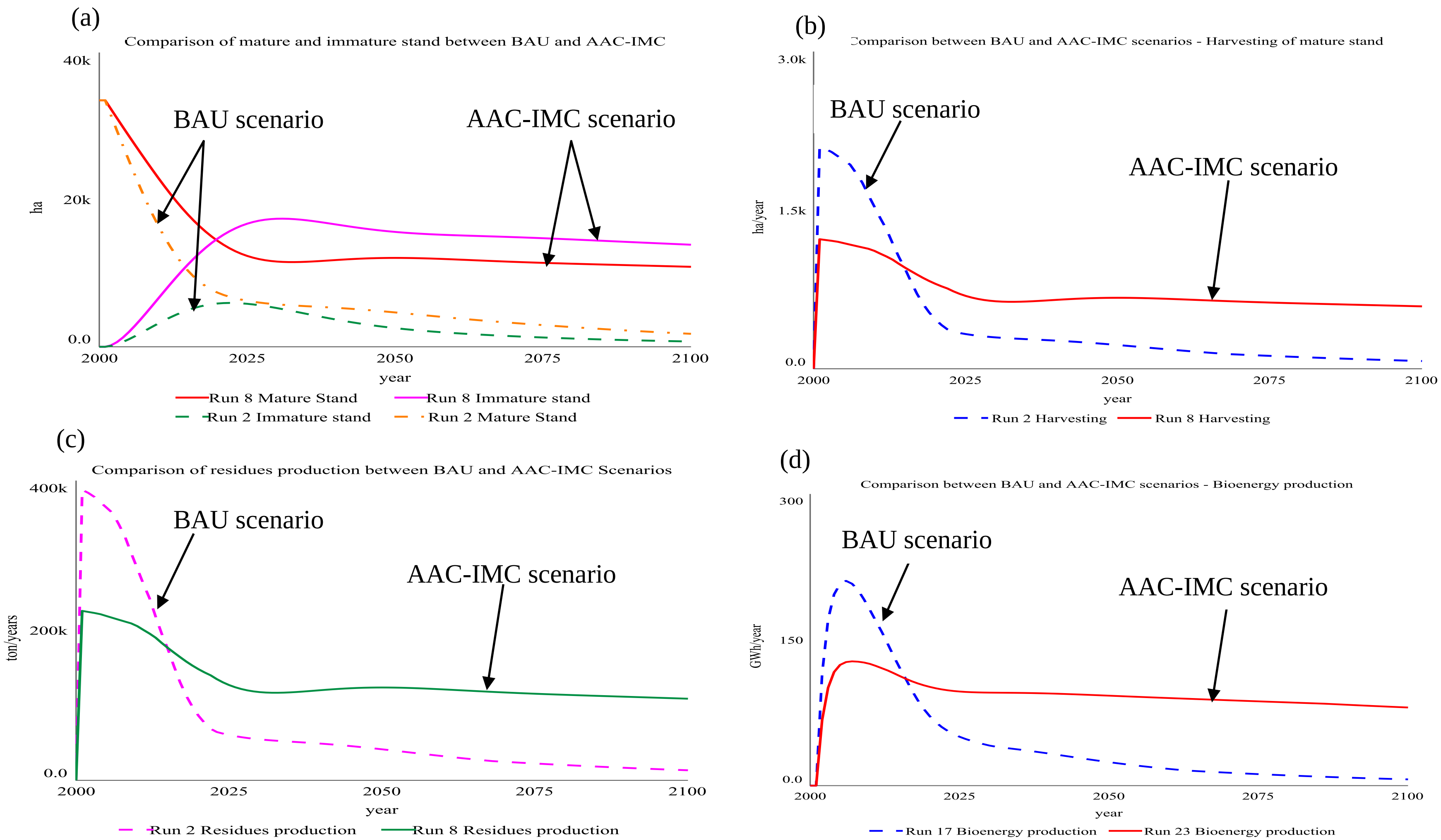

Figure 5.3: Comparison between BAU and AAC-IMC scenario: (a) mature and immature stand, (b) harvesting, (c) primary residues production from the sawmilling process of mature stand and (d) bioenergy production from the residues simulated over a time horizon of 100 years.

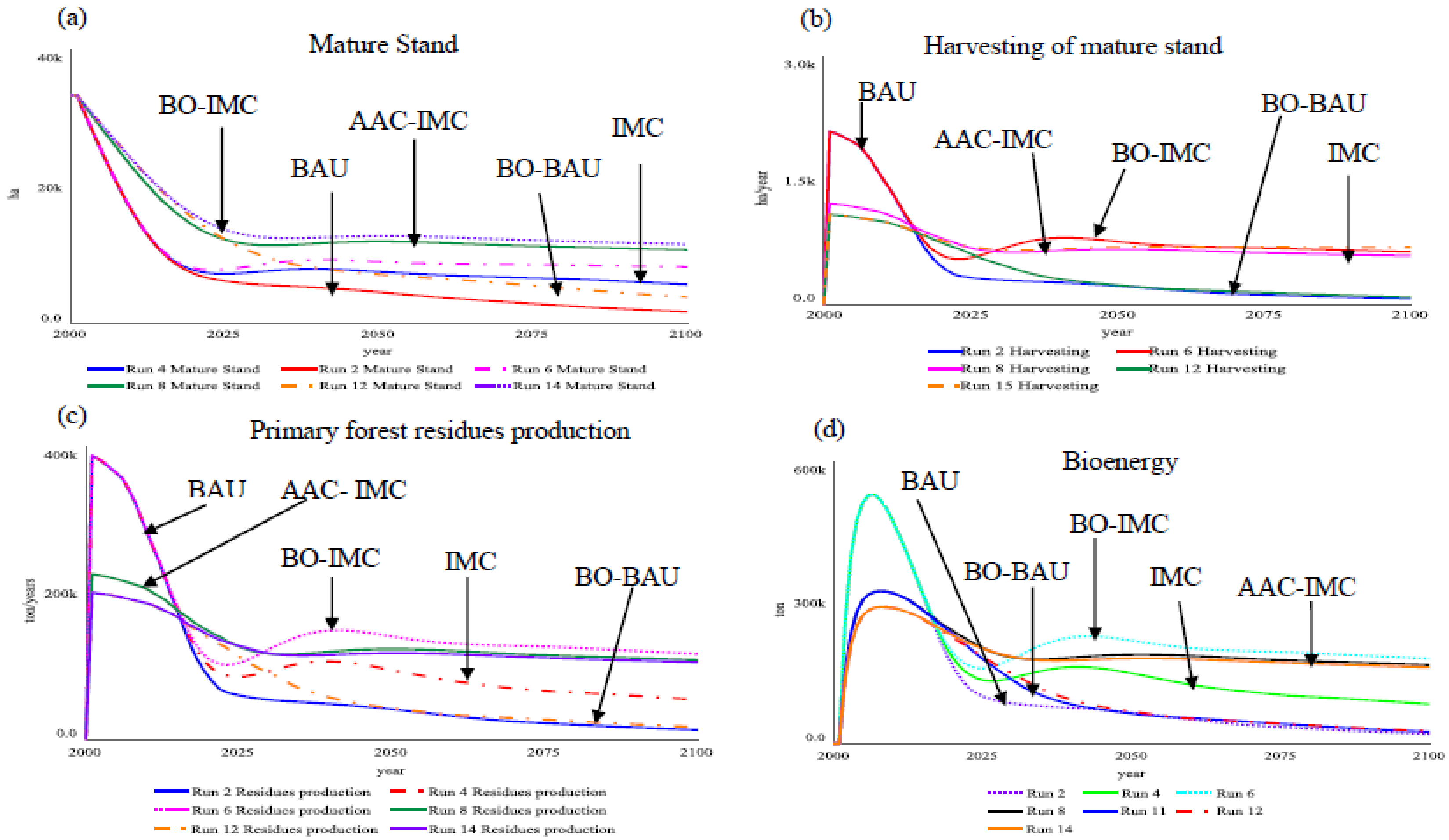

Figure 5.4: Comparison of BAU, IMC, AAC-IMC, BO-BAU and BO- IMC scenario on: (a) mature stand, (b) harvesting, (c) primary residues production from the sawmilling process of mature stand and (d) bioenergy from the residues simulated over a time horizon of 100 years.

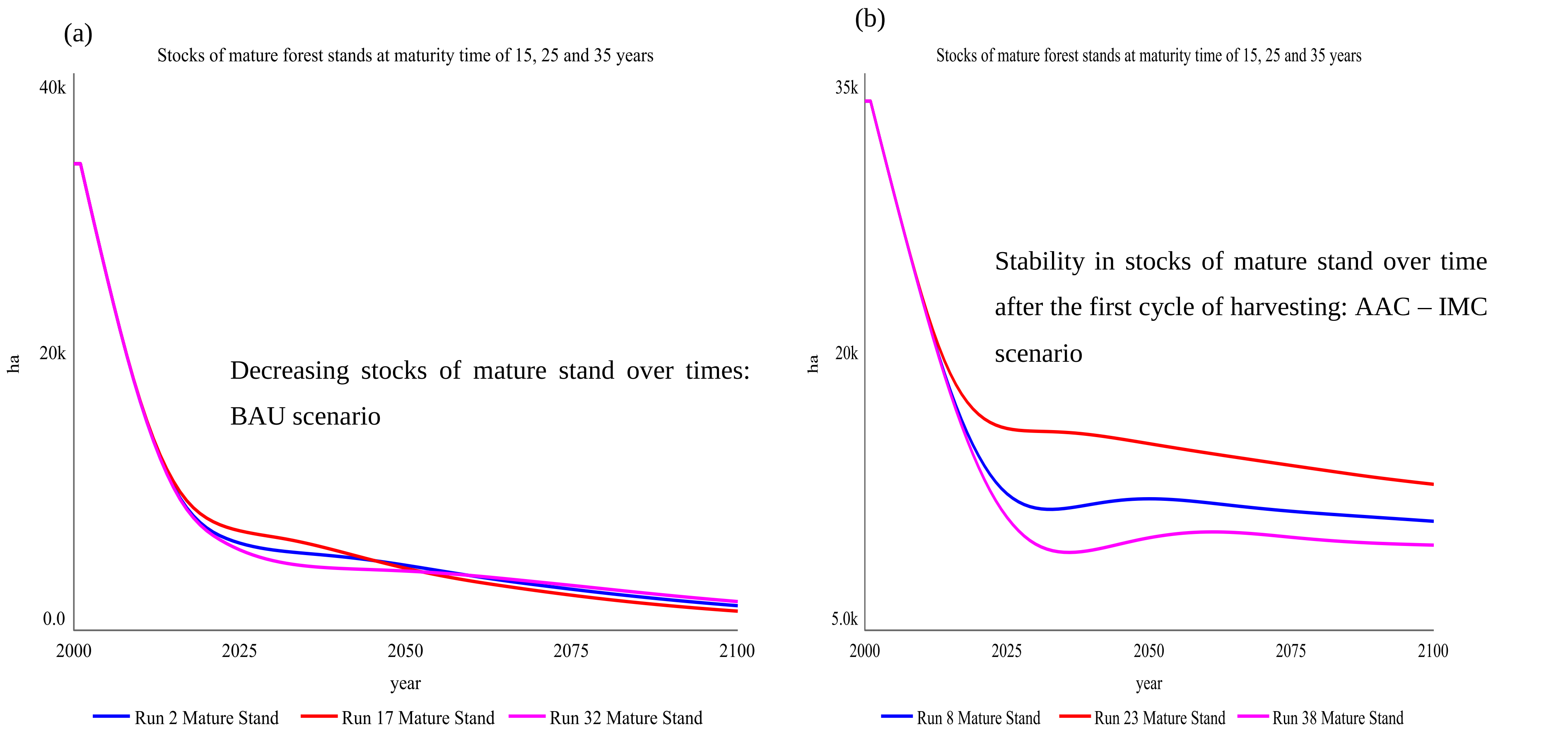

Figure 5.5: Mature forest stand availability for timber production at 15, 25 and 35 years maturity time of trees simulated over a time horizon of 100 years: (a) BAU scenario at 25 years maturity time (Run 2); at 15 years maturity time (Run 17), and at 35 years maturity time (Run 32); (b) AAC-IMC scenario at 25 years maturity time (Run 8); at 15 years maturity time (Run 23), and at 35 years maturity time (Run 38).

The results in Figure 5.5 showed that maturity time of the tree species of 15, 25 and 35 years had no effect on stocks of mature stand over time in the BAU scenario (Fig. 5.5 a). The stocks of mature stand decreased similarly over time from 33501 ha to about 2000 ha in all the three runs representing the three maturity times. However, in the AAC-IMC scenario (Fig. 5.5b), constant availability of more mature forest stands (about 15000) over time for harvesting for timber production could be realised in Run 23 for the15 year-maturity time compared to about 12500 ha and 10000 ha in Run 8 and Run 38 for 25 years and 35 years maturity times, respectively. The three maturity times showed constant availability of mature stands after the first harvesting cycle (2030) up to 2100.

Summary of findings in the primary forest residues value chain

Simulation results of the SAS-Biopro model for the primary forest residues value chain reveal that steady flow of both timber and primary forest residues for bioenergy production can be achieved by synchronising replanting and harvesting, and minimising mortality fraction of replanted young forest stand to ≤ 0.1. Replanting the harvested sites with fast maturing tree species in the forest plantations is not a high leverage solution to promote sustainability of the timber and bioenergy production. Introduction of annual allowable cut, utilisation of efficient logging and sawmilling technologies and increasing resource allocation to plantations management to improve management capacity which in turn can improve silvicultural operations, reduce the death (mortality) fraction of replanted trees, improve monitoring and control of forest fires, monitoring and control of encroachment by the sawyers in the plantations are the key process and policy mechanisms to promote sustainable bioenergy and timber production in the Viphya forest plantations.

5.3 [7]Annual production, availability, bioenergy potential and sustainability of rice residues in rice farms in Karonga district in Malawi.

Annual production of rice residues was estimated from 10-year (2005 – 2014) historical data on rice production obtained from Ministry of Agriculture for Karonga district. Table 5.4 presents the annual production of rice straws and husks for the 10-year period. Residues that can actually be collected from the farms and rice processing mills for bioenergy production, after accounting for losses, can be used to generate 16.64

[7]Detailed results have been presented in Chapter 8, which has been published in a peer reviewed journal with Impact Factor of 8.050

GWh_E if converted to electricity in small-scale biomass gasification systems. An innovative synergetic integration of bioenergy and rice production in rice farms that increases both bioenergy and rice production has been developed as a deployment strategy for rice residues-based bioenergy systems in rice farms.

Synergetic integration approach to deployment of rice residues-based bioenergy in rice farms has demonstrated that the resilience of rice residues production and supply for bioenergy production, availability and reliability of the rice residues-based bioenergy systems, can be promoted by supplying the bioenergy to irrigation pumping for rice production, which increases residues production and supply for bioenergy production. Detailed evaluation and results are presented in chapter 8, which has been published in Renewable and Sustainable Energy Review Journal.

Table 5.4: Historical production of rice residues inKaronga District in Malawi

Year	Rice straws	Rice husks	Total
2005	22020	3346	25366
2006	18069	2746	20815
2007	25673	3901	29574
2008	43960	6680	50640
2009	47602	7234	54836
2010	50178	7625	57803
2011	53395	8114	61509
2012	52663	8003	60666
2013	66634	10126	76760
2014	60973	9266	70239
Mean	44117	6704	50821

5.3.1 Modelling sustainability of rice residues-based bioenergy production

The development process of the SAS-Biopro model for the rice residues-based bioenergy system and the model equations have been presented in Chapter 4. The model consist of three sub models as follow: (i) rice residues and bioenergy production from rain-fed cultivation (wet planting) of rice; (ii) Competing uses of straws; and (iii) Integrated rice and bioenergy production sub models. Figure 5.6 (a) and (b) show the structure and simulation results of the rice residues and bioenergy production from wet planting sub model.

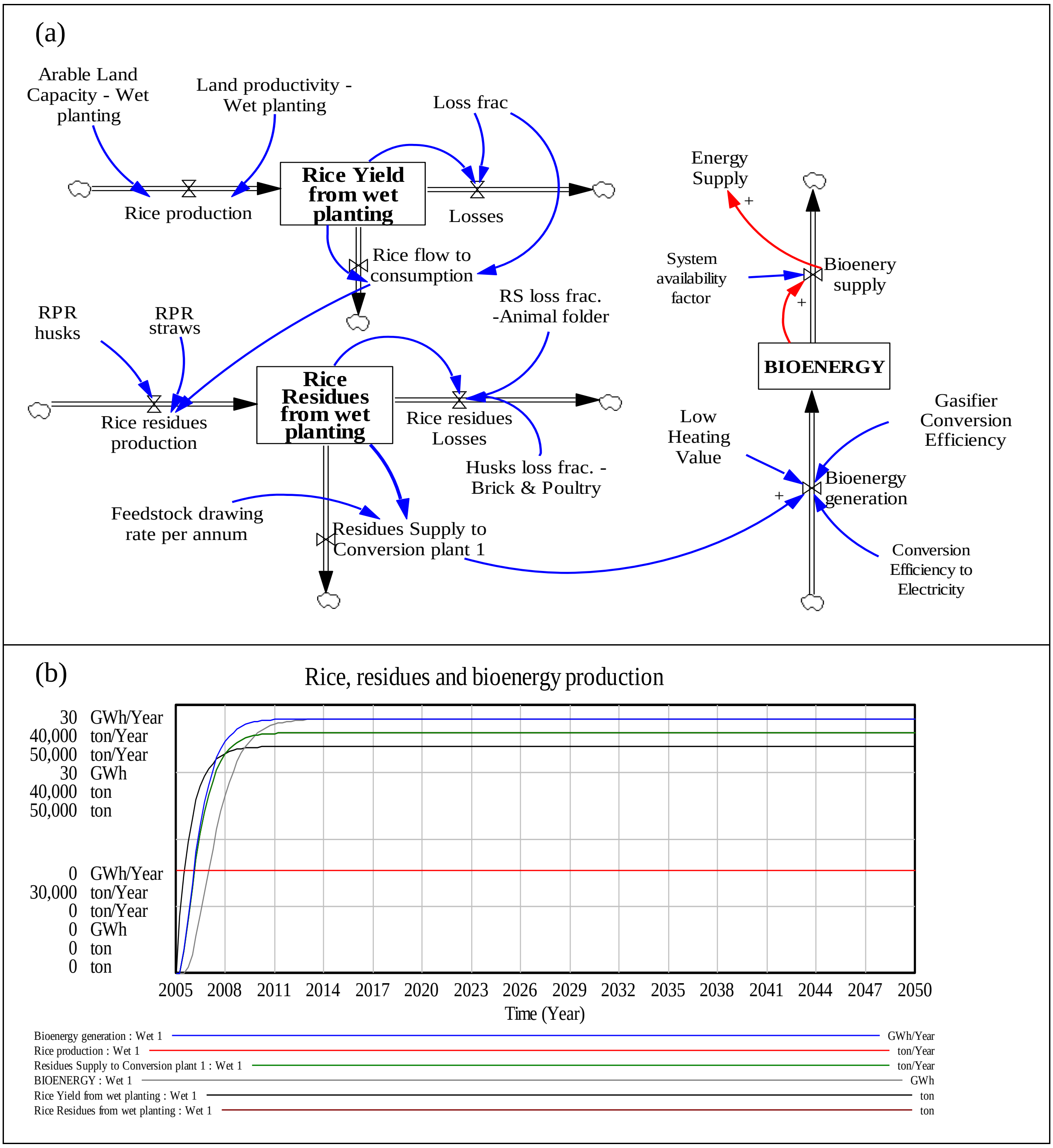

Figure 5.6: (a) SAS-Biopro sub model and (b) simulation results of rice, residues and bioenergy production from wet planting of rice in rice farms in Karonga district in Malawi

The sub model was simulated over a time horizon of 45 years, from 2005 to 2050, for the base case (business as usual) scenario to test the dynamics for three cycles of the minimum lifespan (15 years) of small-scale biomass gasification to electricity system based on assumption that the dynamics in rice production would remain constant after dry planting reached maximum arable land utilisation capacity owing to limitation of suitable arable land for rice cultivation in the district. The base case scenario of the model was simulated based on the following assumptions: (i) maximum arable land (13362 ha) used for rice production is utilised and (ii) the amount of residues used for animal folder (50% of straws), soil conditioning in the rice fields (10% of straws), commercial poultry (25% of husks), curing of bricks (10% of husks) remain constant over the simulation time horizon.

Simulation results presented in Figure 5.6 (b) show increasing rice residues and bioenergy production over time from 2005 to 2011 then remain constant up to 2050. The competing uses of the residues influence variations in the amount of rice residues that can be collected for bioenergy production. For instance, rice straws used for animal (cattle) fodder can influence variations in the amount of the straws that can be collected from the rice farms in Karonga district for bioenergy production. The dynamics in the population of cattle in the district, as a result of cattle population growth rate, mortality rate and off-take (cattle slaughtered for beef) (Huttner et al., 2001), can increase/decrease the demand for animal folder. Table 5.5 shows the population of cattle in Karonga Agricultural Development Division and the estimated population growth rate, mortality rate and the off-take.

Table 5.5: Cattle population growth rate, calves mortality rate and off-take in Karonga Agriculture Development Division

Commodity	Karonga Agriculture Development Division				
All cattle	2011/12	2012/13	Estimated cattle population growth rate	Estimated calves mortality rate	Estimated off-take
Census	155,157	160,565	3.5% (Huttner et al., 2001)	1.4% – 3.2%	5% - 11%
Slaughtables	41,651	43,105			

5.3.1.1 Sources of variations in stocks of rice straws for bioenergy production

Variability in stocks of rice straws and husks that can be collected from the rice farms for bioenergy production can influence transient production of bioenergy based on the residues supply chain. As discussed in section 2.7 in Chapter 2, steady flow of feedstock to a prime mover in energy generation is an essential requirement for stability, availability and reliability of the energy supply system (Moriarty & Honnery, 2007). Therefore, a SAS-Biopro sub model, presented in Figure 5.7, was developed to assess the influence of animal population on long term availability of the rice straws for bioenergy production. The results in Figure 5.8 (a) show that the increase in animal population increases the rice straws used for animal fodder that decreases the amount of the straws collected for bioenergy production over time. Results from sensitivity analysis (Figures 5.8b, c and d) of cattle population growth rate, calves mortality rate and the off-take for beef for Karonga district, simulated over a similar time horizon of 45 years as the base case scenario presented in 5.3.1 above, show that exponential growth of the cattle population after 2028 increases the demand for animal fodder that surpasses the amount of straws produced from rain-fed rice cultivation.

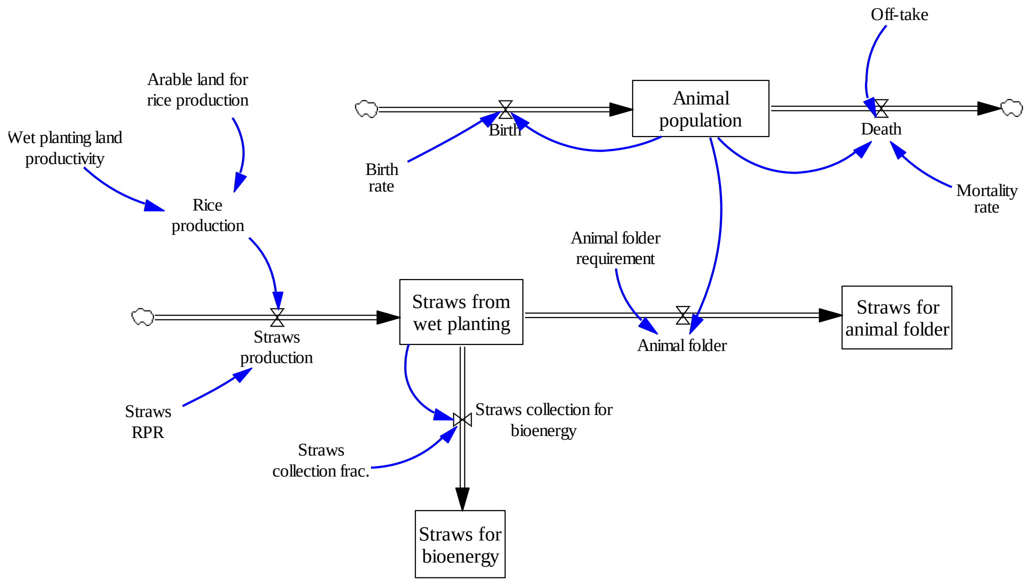

Figure 5.7: SAS-Biopro sub model structure for simulation of the impact of animal population on rice straws for bioenergy production in rice frams in Karonga district.

Rice production can be increased by extensive rice farming and by double-cropping of rice per annum. Limiting conditions for expansion of arable land for rice cultivation have been discussed in section 2.6. However, the lack of energy that can be supplied to irrigation water pumping has been identified as a limiting unit operation to promote double-cropping of rice per year in the rice farms. Rice residues from the rice farms can be utilised to promote double-cropping of rice if converted to generate electricity that can be supplied to irrigation water pumping in the rice farms.

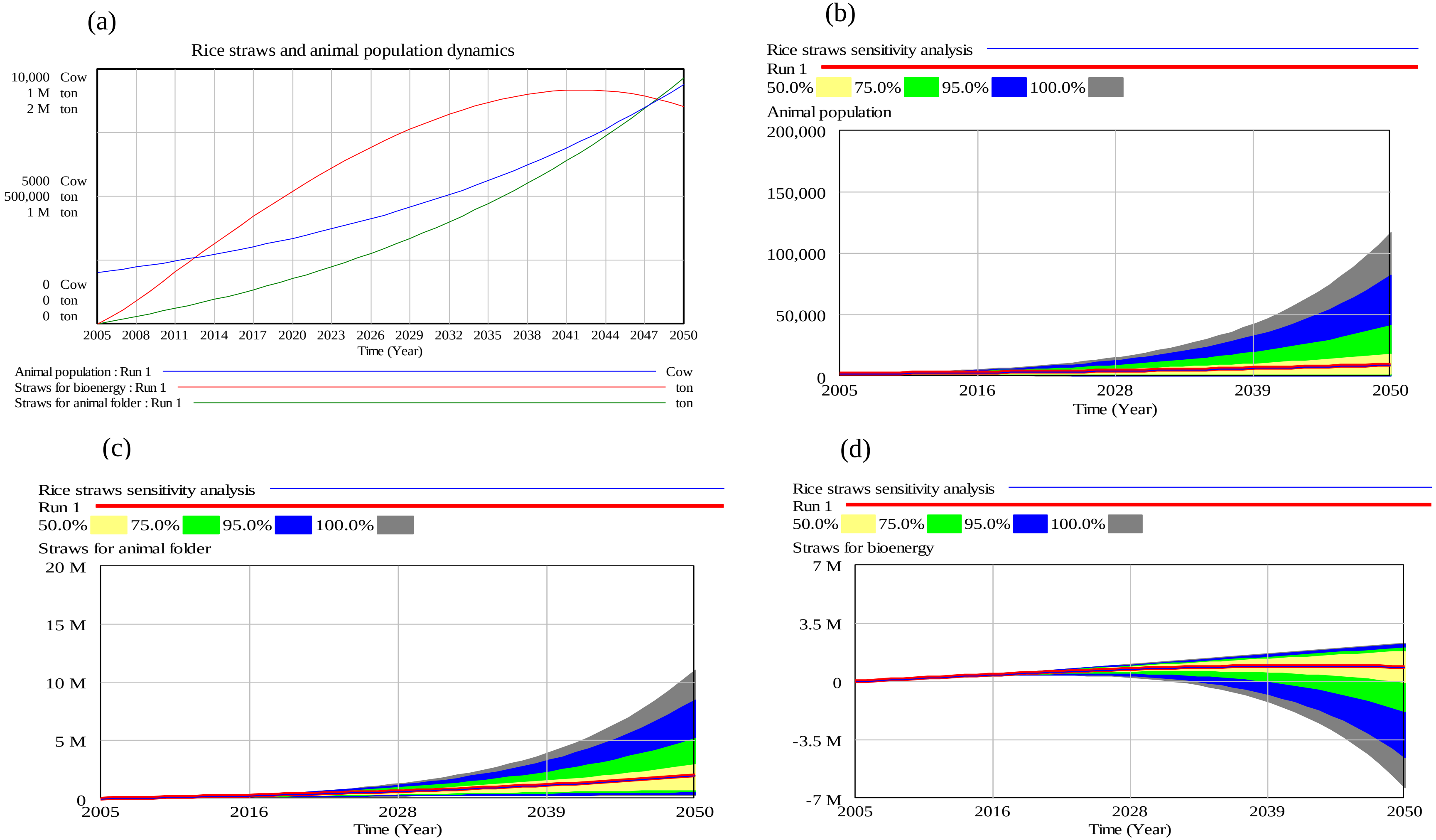

Figure 5.8: Rice residues dynamics as a result of competing use as animal fodder (a) increase in rice straws used for animal fodder animal population, (b) animal population sensitivity analysis over time, (c) rice straws for animal folder over time, (d) depletion of rice straws with increasing demand for animal fodder.

As observed is section 2.8, bioenergy production from rice residues is not a new phenomenon. However, a deployment strategy that can simultaneously promote sustainable bioenergy and rice production in the rice farms has been lacking. Rice residues that remain in the rice farms and processing mills can be utilised to generate bioenergy, which can be supplied to the rice farms to promote rice production. Therefore, a synergetic integration of bioenergy and rice production has been developed in this study as an innovative deployment strategy of rice residues-based bioenergy production, to promote double-cropping of rice per year in the rice farms. The strategy is presented and discussed in detail in Chapter 8 of this dissertation, which has been published in a peer reviewed journal.

5.3.2 Integration of bioenergy in rice farming system

A sub model for integrated bioenergy and rice production in rice farms, given in Figure 5.9, was developed to assess the flow of rice residues from double-cropping of rice and bioenegy production over time. In the sub model, rice residues that remain in the rice farms and processing plants, after accounting for the residues used for the competing uses, are supplied to a bioenergy conversion plant to generate electricity which is supplied to irrigation of the rice farms.

Sensitivity analysis was performed to test the sensitivity of the model to changing parameters. Sensitivity analysis was perfomed by varying the loss fractions between 0 and 1 of the rice residues, which are characterised by uncertainities in demand for animal feed, commercial poultry and brick curing. As observed in Figure 5.8 (a), straws used for animal feed influnced the variations in the amount of straws that can be collected for bioenergy production over time. Figure 5.10 (b), (c), (d), (e) and (f) show the results of senstivity analysis of the integrated bioenergy and rice production sub model simulated the time horizon of 45 years. The residues generated from rice production from irrigated land (dry planting) are supplied to the bioenergy plant for generation of more electricity. The results from simulation of the sub model, presented in Figure 5.10(a), indicate the potential of increasing bioenergy and rice production over time.

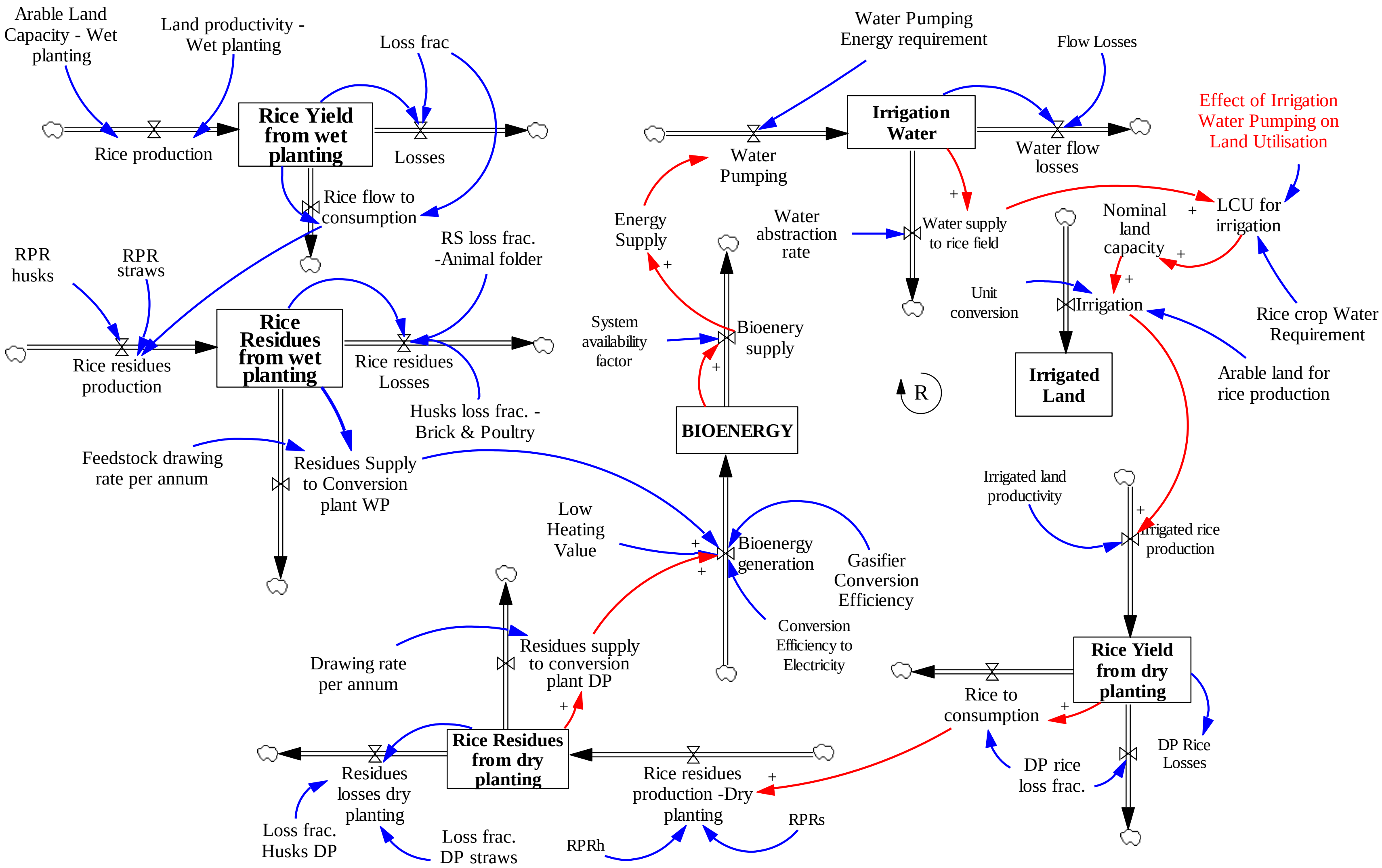

Figure 5.9: SAS-Biopro sub model structure for integrated bioenergy and rice production in rice frams in Karonga district.

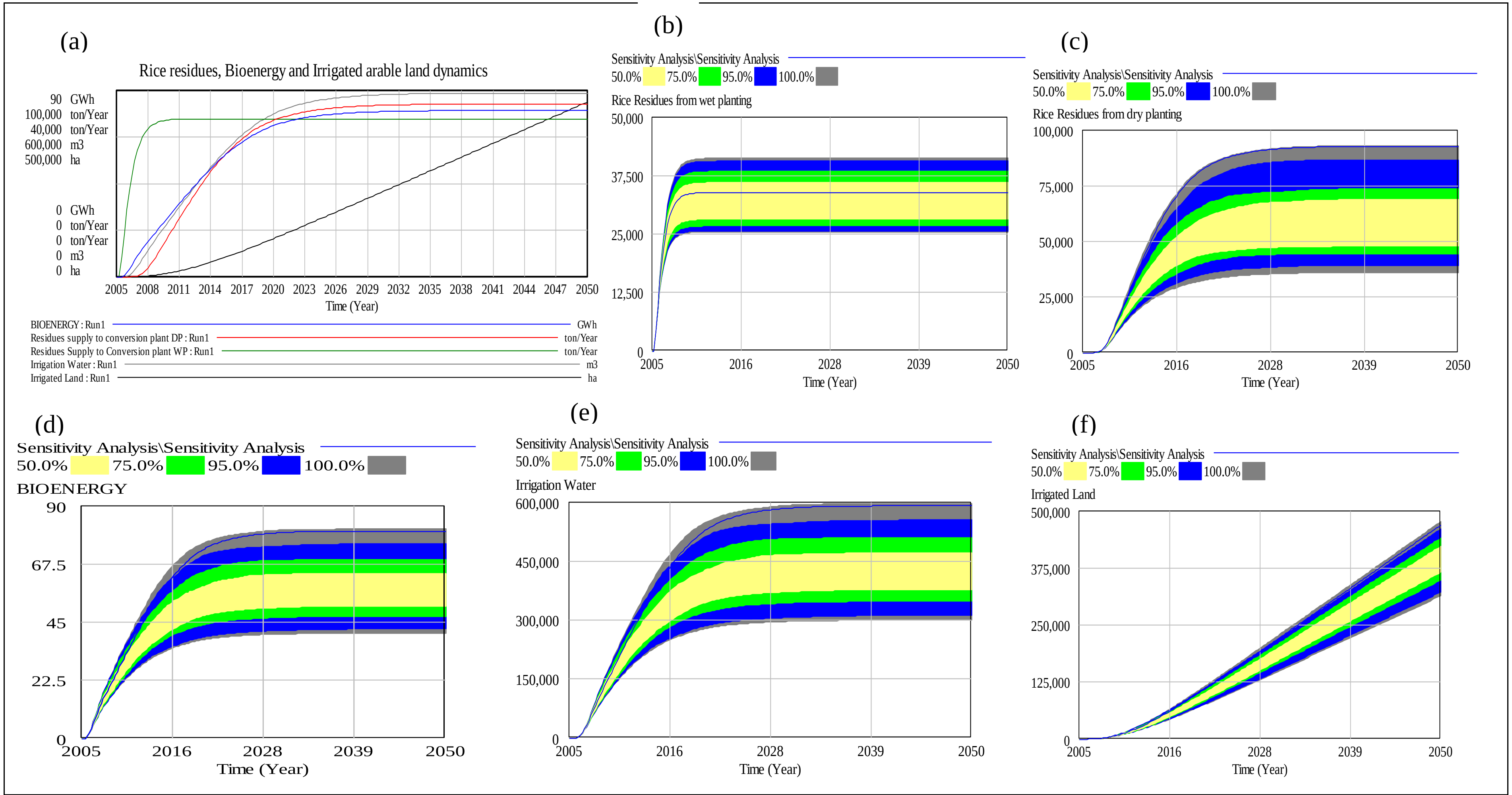

Figure 5.10: Rice residues and bioenergy production in an integrated bioenergy and rice production simulated over 45 years: (a) rice residues from wet planting, (b) sensitivity analysis of rice residues from wet planting, (c) rice residues from dry planting, (d) bioenergy, (e) irrigation water and (f) irrigated land over time

5.4 Chapter summary

In this chapter, results from field and onsite assessment on quantities and bioenergy potential of primary forest residues from Viphya forest plantations and rice residues (straws and husks) from rice farms in Karonga district have been presented. In addition, simulation results of the systems approach model for sustainable production of bioenergy (SAS-Biopro model), for the two feedstock value chains, have been presented. The simulation results include:

- the results of the base case scenarios, presented as business as usual (BAU) scenario in the SAS-Biopro model for the forest residues value chain; rain-fed (wet planting) scenario for the rice residues value chain;
- simulation results of process innovations in management and harvesting systems in forest plantations presented as annual allowable cut and improved management capacity (AAC-IMC) scenario for the forest residues value chain;
- integrated bioenergy and rice production scenario in rice farms for the rice residues value chain; and
- sensitivity analysis results of the models for the two residues streams.

Implementation of annual allowable cut of 1240 ha of mature forest stand, replanting rate of 100% of the annually harvested area and minimisation of trees mortality fraction to less than 0.1 per annum can promote long term availability of mature forest stands for harvesting for timber production and primary forest residues for bioenergy production. The approach promotes sustainability of both timber and bioenergy production over time, and supports sustainable forest management.

The results from simulations of the SAS-Biopro model for the rice residues value chain have shown that targeted supply of bioenergy generated from rice residues to irrigation water pumping for rice production in the rice farms increased annual rice and rice residues throughput to about 75000 air-dried tonnes per cropping season of dry planting from about 44000 air-dried tonnes from wet planting. Bioenergy production increased to about 80 GWh. Economic viability evaluation of small-scale (250 kW) biomass gasification to electricity system has been presented in 6.3.3 in Chapter 6 for the forest residues and in 8.33 in Chapter 8 for the rice residues value chains.

Chapter 6: Whole systems integration of bioenergy and timber production in timber plantations

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Title: Whole systems integration of bioenergy and timber production in timber plantations

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Objectives and summary of findings in the chapter

This chapter presents the work carried on objectives (i) and (iii) of the research, specifically on primary forest residues value chain. The chapter contributes a multi-methods approach that combines the conventional forest residues inventory, bioenergy potential and macro-economic viability evaluation with a layered five-step sustainability analysis and the soft systems modelling methods to assessing sustainability of bioenergy production from primary forest residues. In addition, the chapter contributes an innovative process of synchronising harvesting of forest mature stands for timber production and annual feedstock requirement of a primary forest residues-based bioenergy generation plant. The approach promotes sustainable integration of timber plantations management and the forest residues-based bioenergy systems. The process is based on re-evaluation of annual allowable cuts in timber plantations within the constraints of the plantations area, maturity age of predominant tree species and sizing of the bioenergy plant scale based on residues throughput generated from an annual allowable cut of mature forest stand.

6.1 Introduction

Bioenergy production and utilisation has increased in recent decades driven by environmental awareness to reduce greenhouse gas emissions from use of fossil fuels, declining supplies of the fossil fuels and the need to enhance energy security (Buchholz et al., 2007; McKendry, 2002b). Within the renewable energy mix, bioenergy possesses added advantages beyond low carbon and clean energy compared with wind and solar given that bioresources can be controlled and adjusted in production and different forms of bioenergy products can be produced, stored and deployed to end use processes when needed (Heidenreich S., Foscolo, 2015). Bioenergy can promote energy and food security and contribute to the development of rural economy through production and mobilization of feedstocks such as forest and agro residues where these bioresources are locally produced (Muth et al., 2013; Yan & Lin, 2009; Cambero et al., 2015).

Studies have shown that primary forest (logging) residues from timber production in forest plantations can provide the renewable bioresource for production of liquid transport fuels, heat and electricity that can contribute to secure and sustainable energy supply to end use processes (McKendry, 2002; Cambero et al., 2015; IEA, 2012 p222; Haberl et al., 2010; Sasaki et al., 2009; Rossillo-Calle et al., 2007; Smeets & Faaij, 2007; Hoogwijk et al., 2003). It is estimated that forest plantations constitute 3% of the world forests consisting of 60 million and 55 million hectares in developed and developing nations respectively (Hartley, 2002). The forest plantations are harvested for wood products mostly timber, pulp or round logs wherein significant quantities of primary forest residues are produced.

Characteristically, primary forest residues are low cost and have low risks (Gan & Smith, 2007). Availability of the residues in forest plantations located in rural areas in developing economies provides opportunity for the development of bioenergy systems with benefits that can also be accrued to low income rural communities surrounding the forest plantations which lack access to modern forms of energy.

Viable processes and scale of conversion plants of forest residues to modern forms of energy depend largely on energy needs of the end use processes and the size of the residues supply chain. Iye & Bilsborrow, (2013) Jiang et al., Scarlat et al., (2012); McKendry, (2002b) have argued that sustainability of the forest residues supply chains depends on the accurateness of the estimation methods to determine potential availability and size of the supply chains, which is a precursor technical aspect to the development of viable forest residues based bioenergy systems. However, the dependency of production and availability of primary forest residues on timber production, which in turn depends on the demand for timber, availability of stocks of mature stand and technologies used for harvesting the mature stand in timber plantations can influence variations in production and supply of primary forest residues for bioenergy production. In addition, site specific management and harvesting systems of forest plantations, fragmented approach to bioenergy production from forest residues in the sectoral policies of energy and forest sectors (Kaunda, 2013) can exacerbate the variations in stocks of mature stand in the plantations for timber production and therefore availability of primary forest residues for bioenergy production. Variations in availability of primary forest residues can further dissuade investment in bioenergy production from the residues.

Furthermore, Eswarlal et al., (2014); Zalengera et al.,(2014); Domac et al.,Rösch & Kaltschmitt, (2005); Costello & Finnell, (1999) have highlighted the significant influence of stakeholders' participation in planning development of bioenergy projects on acceptability and sustainability of bioenergy systems. Therefore, a holistic stakeholders' analysis in timber and bioenergy production systems can promote identifying the key stakeholders, their interest, power and influence in timber plantations management, timber production, residues supply chains and bioenergy production which can be the potential opportunities or barriers to the development of primary forest based bioenergy systems. Sustained interest and involvement of key stakeholders surrounding timber plantations and in the sectors of forestry and energy can provide the opportunity to develop sustainable primary forest residues based bioenergy systems. Site-specific sources of variations in stocks of mature stand in timber plantations and in primary forest residues supply chains need to be understood to support development of innovative approaches that can promote resilience of the residues supply chains and enhance the availability factor and reliability of the bioenergy systems utilising the forest residues for feedstock.

This study has evaluated whole system integration of bioenergy and timber production from primary forest residues to simultaneously promote steady production, availability and flow of timber and primary forest residues, and bioenergy production using a case study of decentralised small-scale downdraft gasification systems for electricity generation in 33501 ha of pine trees in Viphya forest plantations (Fig. 1.2a in Chapter 1) in northern Malawi. The study has investigated the technical, economic, environmental, social and policy impacts of the forest plantations management and harvesting systems on primary forest residues based bioenergy systems using a combination of onsite inventory, discounted cash flow, sustainability analysis and soft systems modelling (SSM) on the residues value chain. The paper contributes this multi-methods approach that combines the conventional forest residues inventory, bioenergy potential and macro-economic viability evaluation with a layered five-step sustainability analysis and the soft systems modelling methods to assessing sustainability of bioenergy production from primary forest residues.

Onsite inventory provided opportunity to evaluate site specific forest plantations management and harvesting systems, taking into account the logging and sawmilling technologies and the residues to product ratio. Application of a layered five-step sustainability analysis provided opportunity to show the level of power/influence and interest of key stakeholders, the environmental, economic, social, technical and regulatory impacts along the value chain of bioenergy production from primary forest residues. Application of soft systems modelling enabled demonstration of the interconnectedness of components of the bioenergy system with the stakeholders in forest plantations management, energy generation, supply and regulation and end use processes which reveals the enablers and disenablers along the bioenergy value chain, categorized as technical, socio-economic, environmental and regulatory impacts on stocks of mature stand and residues production.

The paper provides strategic information useful to policy makers in energy and forestry sectors and investors in bioenergy for development of primary forest residues-based energy generation systems that can simultaneously contribute to sustainable forest plantations management and bioenergy production. Factors that can promote or limit the integration, points of high leverages along the bioenergy production value chain that require policy intervention to sustain bioenergy and timber production as an integrated unit system and forest plantations management innovations required to promote the integration have been provided. The multi-methods approach used to investigate systems integration of bioenergy and timber production in this study can be adapted for assessing integration of individual bioenergy systems based on primary forest residues for feedstock within their specific geographic, ecological, societal, and technological context and scale, especially in developing economies where availability of reliable data is challenging.

6.1.1 Background of the case study area and the Viphya forest plantations

The Viphya forest plantations (Fig. 1.2a in Chapter 1) consist of 53501 hectare of pine (*Pinus patula* and *Pinus kesiya*) trees located in northern Malawi (Ngulube et al., 2014). The plantations form the single largest block of the pine trees, which have been in the first cycle of harvesting and replanting since 2001 (Kafakoma & Mataya, 2009). About 20 000 hectares of the plantations are managed by a private wood industry (RAIPLY) through concessionary agreement with the Government of Malawi (GoM) (Zalengera etal., 2014; Ngulube et al., 2014; Kafakoma & Mataya, 2009) and 33501 hectares are managed by GoM through the Department of Forestry (DoF) where mature stand are sold to small and medium forest enterprises (SMFEs) (Kafakoma & Mataya, 2009). SMFEs harvested mature stand by clear cut method using mobile sawmilling technologies (Wood-Miser and AMEC mills) (Kafakoma & Mataya, 2009).

Primary forest residues that are produced in logging and sawmilling operations in the plantations provide the opportunity of developing bioenergy systems that can contribute to secure and sustainable energy supply to the rural resource-poor communities having limited access to modern energy products such as electricity in Malawi (Malawi National Energy Policy, 2003). Rural communities around the Viphya forest plantations provide a potential market for the bioenergy generated from the residues. Bioenergy generated from the residues from timber production in the plantations can be supplied to the low-income households and some social services such as schools, clinics and telecommunication in the communities.

6.2 Materials and Methods

A multi-methods approach (section 6.1) that combines the conventional forest residues inventory, bioenergy potential and macro-economic viability evaluation of bioenergy systems with a layered five-step sustainability analysis and the soft systems modelling methods was used in this study to assess sustainability of bioenergy production from primary forest residues

6.2.1 Materials

The materials used for the study included semi structured questionnaires that were used for data collection from plantation management and stakeholders including DoF, SMFEs, transporters and households in rural communities around the plantations. In addition, the resource flow sheet was used for onsite inventory of the residues at the SMFEs to validate the data obtained from plantations management reports. The Materials used and related activities in the study are summarized in Table 6.1.

6.2.2 Methods

A combination of literature review and onsite inventory provided background data for simulation using soft systems modelling approach and performing discounted cash flow, and sustainability analysis to assess the challenges emanating from primary forest residues production and management and utilization thereof on bioenergy production and sustainability of the forest residues as feedstocks.

Table 6.1: Materials used for data collection and onsite assessment of residues production

Material	Function	Source
Management reports and literature	Source of data production harvesting and replanting of plantations	Onsite
Questionnaires	Data collection from policy makers, sawyers, rural households and other potential stakeholders	Developed for the study
Resource flow sheet	Recording inflows and outflows of the forest residues	Onsite
Measuring tape	Log dimension measurement	
Wood-Mizer LT 20	Timber harvesting	SMFEs in Viphya plantations
Plastic bucket (0.07 m^3)	Volume of generated sawdust	Acquired for the study
Beam balance	Weight of sawdust	Acquired for the study
Chainsaws	Comminution of the residues	Hired from SMFEs
Statistical Package for Social Scientists	Data analysis	Stellenbosch University
Vensim software	Causal loop modelling	Acquired for the

study

6.2.2.1 Production and availability of primary forest residues

Annual tree replanting and harvesting rates and cycles for a period of 15 years (2001-2015), harvesting systems, logging and sawmilling technology efficiencies and residue production ratios were estimated from the plantations management reports and literature (Ngulube et al., 2014; Kafakoma & Mataya, 2009 Openshaw; 2010). The data provided historical trend for timber and residues production, availability and flow of residues to competing uses and stocks of mature and young stands. Additional information on plantations capacity and management systems was collected from Department of Forestry regional and Viphya plantations offices through interviews and formal discussion groups using a semi structured questionnaire. The data was validated onsite in the Viphya forest plantations by collecting real time data on timber logging and production by SMFEs located at Chitheka 2, east of Mazamba (Fig. 1.2 in Chapter 1). The annual production of primary forest residues was compared at two levels: (i) by source of the data and (ii) by the technology used in harvesting and processing of the timber, thus, AMEC and Wood-Miser mills.

Annual production of primary forest residues was estimated using equation (6.1) from literature (Hoogwijk et al., 2013; Smeets & Faaij, 2007) on the data of timber production and residues generation fraction of AMEC and Wood-Mizer milling technologies obtained from management reports.

$$V_{RT} = \left(\frac{(TY_{/ha} \times RPR)}{TF} \right) N \tag{6.1}$$

Where:

V_{RT} is the total volume of residues produced per annum in m^3;

$TY_{/ha}$ is timber yield per hectare of a harvested stand in m^3;

RPR is the residues to product ratio (dimensionless);

TF is timber production fraction (dimensionless); and

N is total number of hectares harvested per annum (dimensionless).

Onsite validation involved assessing residues from a sample of 56 logs from 154 logs using procedures reported in (West, 2009; Avery & Burkhart, 2002 p101) that measured diameters for each log; at the base, middle and tip using measuring tape. The total volume of the logs was calculated using Newton's Cubical Volume equation given as equation (6.2) with minor modification.

$$\text{Newton's Cubical Volume} = \sum \left(\frac{(B + 4B_{½} + b)}{6} L \right) \qquad (6.2)$$

Where:

B is the cross-section area at the base (m^2)

$B_{½}$ is the cross-section area at midpoint (m^2)

b is the cross-section area at the tip (m^2)

L is the log length (m)

The logs were split into timber (0.05 m x 0.15 m x 5.5 m), using Wood-Miser LT20 sawmilling technology. The volume of residues was estimated using (Equation 6.3).

$$V_R = NCV - V_T \qquad (6.3)$$

Where:

V_R is volume of residues (m^3)

NCV is Newtonian Cubical Volume of the logs (m^3)

V_T is volume of timber produced from the logs (m^3)

The residues generation fraction was calculated using equation (6.4)

$$R_f = \frac{V_R}{NCV} \qquad (6.4)$$

Where:

R_f is residues fraction of the logs sawn into timber.

V_R is volume of residues (m^3)

NCV is Newtonian Cubical Volume of the logs (m^3)

The quantity of sawdust produced was estimated as the product of the number of pre-weighed buckets filled with sawdust and the volume of the bucket in cubic meters. The mass of the sawdust was calculated as the difference between the mass of the bucket filled with sawdust and the mass of the empty bucket in kilograms (equation 6.5).

$$M_{sd} = (M_{bsd} - M_b)N_b \qquad (6.5)$$

Where

M_{sd} is mass of sawdust (kg)

M_{bsd} is mass of bucket and sawdust (kg)

M_b is mass of bucket in (kg)

N_b is total number of buckets filled with sawdust

Small round wood, rejected logs, branches and twigs with diameters > 4cm, were cut into 2 m lengths using chainsaws operated by two casual workers, which were stacked in piles (2 x 2 x 1 m) on the harvest site. The amount of residues was estimated using equation (6.6) and was attenuated by a factor of 0.6 to obtain the equivalent volume of solid wood (Francescato et al., 2008).

$$V_{TP} = (V_P \times N_P)0.6 \qquad (6.6)$$

Where:

V_{TP} is the total volume of all the piles made per ha (m^3)

V_P is the volume of 1 pile (m^3)

N_P is the number of piles per ha in (m^3)

Braches and twigs smaller than 4 cm in diameter and tops that would require baling were excluded in the analysis.

6.2.2.2 Estimation of bioenergy potential of primary forest residues

The bioenergy potential of the residues was estimated using a mean low heating value of 15 GJ/ton obtained from Rossillo-Calle et al., (2013; Francescato et al., (2008); Rossillo-Calle, (2007) using equation (6.7) as reported by Rösch & Kaltschmitt, (1999) with minor modification.

$$Q_{PFR} = (PFR_T \times LHV) \qquad (6.7)$$

Where:

Q_{PFR} is the bioenergy potential of primary forest residues (MJ)

PFR_T is the total primary forest residues collected from the plantations (tons)

LHV is the lower Heating Value of the residues (MJ/kg.)

6.2.2.3 Cost of electricity and profitability analysis

The cost of electricity generated from the residues was evaluated using five small-scale gasifiers rated between 250 and 1250 kW_E coupled with internal combustion engines with output power of 200 to 1000 kW_E being operated within a radius of 50 km from the plantations. Profitability of the investment was evaluated using the discounted cash flow criterion (Turton et al., 2013 pp263-271) using parameters given in Table 6.2 to determine payback period of the investment.

Table 6.2: Factors[1] for evaluation of generation cost and profitability of electricity from primary forest residues within a 50 km radius from Viphya plantations

	Plant scale (kW_E)				
Description	**250**	**500**	**750**	**1000**	**1250**
Gasifier type	Downdraft	Downdraft	Downdraft	Downdraft	Downdraft
Engine make & model	Cummins GTA1710 G	Cummins GTA1710 G	Cummins GTA1710 G	Cummins GTA1710 G	Cummins GTA1710 G
Electrical efficiency (%)	24.5	24.5	24.5	24.5	24.5
Total Capital Cost (US$/yr.)	447982.15	666,648	910,032	1,136,538	1,290,514
Biomass feedstock at 10 to 15% mc[2] (ton/yr.)	4380	8760	12264	15768	17520
Drying (10 to 15% mc)[2]	Air dried	Air dried	Air dried	Air dried	Air dried
Annual energy yield (GWh)	1.58	3.15	4.73	6.31	7.88
Annual Operating Cost (US$)	238146.81	359216. 48	470903.18	578933.16	641771.26

[1]Sourced from suppliers of gasifier; web page: - www.radheengineering.com

[2]Moisture content

6.2.2.4 Sustainability of bioenergy from primary forest residues

A layered five-step sustainability analysis framework that includes stakeholder and impact assessments (Ashby, 2016) was used in combination with data collected from the field survey in Viphya plantations and surrounding communities to assess long term availability of the residues supply chain. The interconnectedness, interactions and interdependence of social factors that can influence variation of residues availability over time were depicted from causal loop diagrams drawn using Vensim software [Buchholz et al., 2007; Maani & Cavana, 2007, Senge & Sterman, 1992; Forrester et al., 1976).

6.2.2.5 Stakeholder analysis

Stakeholders for the forest plantations management and bioenergy production value chains presented in Table 6.3 were purposefully identified based on their professions, roles and responsibilities in the institutions interrelated to energy, forestry and rural community development in the case study area. The study area covered Elamuleni rural community in the peripheral of the Viphya forest plantations and in Mzuzu City (Fig. 1.2 in Chapter 1) where forest residues are sold for firewood and for materials for construction. Key socioeconomic sustainability indicators such as roles and level of influence, interest, concerns, commitment and motivation of the stakeholders to participate in bioenergy production, and job and business opportunities in bioenergy from the residues value chain were captured using structured and semi-structured questionnaires and group discussions.

Power and influence of the stakeholders in the supply chain was determined by the level of participation in decision making and management of the forest plantations, involvement in formulation and review of forestry and energy sectoral policies, roles in reuse or disposal of the residues, and socio-economic benefits from value chain. A total of 184 respondents participated in the survey. Additional technical data was collected from sawyers, timber merchants, traders, transporters and community members. The data was analysed using SPSS and Microsoft excel.

Table 6.3: Categories of stakeholders in the bioenergy production from primary forest residues value chain

Stakeholders	**Frequency**	**Percent**
Sawyers	29	15.8
Household heads	98	53.3
Policy makers (energy, forestry, agriculture)	10	5.4
Transporters	16	8.7
Community leaders	7	3.8
Civil society organisations leaders	2	1.1
Sellers of forest residues	22	12.0
Total	184	100.0

6.2.2.6 Articulation of bioenergy development from forest residue

Articulation and scale for development of bioenergy systems in Malawi was obtained from the Malawi Energy Policy, Biomass Strategy for Malawi, the Energy Demand Assessment Report for Malawi, and the Bioenergy and Food Security Roadmap for Malawi (Malawi Roadmap for Action towards Sustainable Bioenergy Development and Food Security Report, 2013; Energy Demand Assessment Report, 2011; Malawi Biomass Strategy final report, 2009; Malawi National Energy Policy, 2003). The policy documents provided the targets set by the government of Malawi (GoM) for the biomass energy sub sector to reduce consumption of traditional biomass from 93% to 30% while increasing energy production and consumption from renewable sources from 0.2% to 10% by 2050.

6.2.2.7 Environmental and socio economic impacts

Environmental and socio-economic impacts were evaluated from onsite assessment of the amount and costs of fossil fuels, carbon emissions and energy from the fuels, and labour costs for mobilizing primary forest residues from one hectare of harvested mature stand. Chain saws were used for cutting round logs and branches into sizes that could be collected by casual workers. Two casual works were hired to operate the chain saws which used 80 litres of petrol to clear 1 hectare of harvested mature stand. About 20 litres of diesel per trip of 7 ton truck load and 7 casual workers were used for collecting, loading and offloading the barks and round logs, which were transported to Mzuzu city located at a distance of about 50 km from Northeast of Mazamba in the plantations (Fig. 1.2 in Chapter 1).

Carbon emission was estimated using equation (6.8) while as the embodied energy was estimated using equation (6.9) from literature (IEA. 2009; APIC, 2009 pp3-29). The maximum routing distance of transport vehicles for the residues was estimated to be within the radius of 50 kilometres from the plantations.

$$CO_{2\,eq} = \Sigma_1^n (Q_{ij} * EF_{ij}) \quad (6.8)$$

Where:

$CO_{2\,eq}$ is the equivalent carbon dioxide emmission from fuel (kg)

Q_{ij} is the amount of fuel *i* used in process *j* in the value chain (litres)

EF_{ij} is the emission factor of carbon dioxide for the fuel *i* used in process *j* in the value chain (kg/litre)

n is the number of processes that use the fossil fuels

$$EE = \Sigma_1^n (Q_{ij} * CV_{ij}) \quad (6.9)$$

Where:

EE is the embodied energy from the fuels in the value (kg)

Q_{ij} is the amount of fuel *i* used in process *j* in the value chain (litres)

CV_{ij} is the calorific value of fuel *i* used in process *j* in the value chain (J/litre)

Transport costs were based on the hiring rates provided by transporters, which were estimated at US$0.65 per ton per kilometre. The labour costs for collecting the residues, loading on and offloading from trucks were estimated from the minimum wage for casual workers in Malawi at US$1.25/day. Thus, the cost of the residues per ton was estimated from the costs of the fossil fuels used in the value chain, hired equipment, labour and transport costs for mobilizing the residues from one hectare of harvested stand to delivery to a bioenergy conversion plant located at 50 km radius from the plantation using equation (6.10).

$$C_{PFR} = \Sigma(C_F + C_E + C_L + C_T)/R_Y \qquad (6.10)$$

Where:

C_{PFR} is the cost the primary forest residues per tonne (US$/ air dried ton)

C_F is the cost of fuels used for mobilising residues from one hectare (US$/ha)

C_E is the cost of hiring equipment for communtion of residues on one hectare (US$/ha)

C_L is the labour cost for comminution, collecting, loading and offloading the residues produced from one ha (US$/ha)

C_T is the transport cost of the residues collected from one hectare in the plantations to a conversion plant site (US$/ha)

R_Y is the residues yield that can be collected from harvested area (ton/ha).

6.2.2.8 Stakeholders' perception and interest in primary forest residues supply chain

The impacts of stakeholders' perception and interest in primary forest residues supply chain was mapped from stakeholders' analysis data, from the categories presented in Table 5.3, using causal loops plotted in Vensim software. Mapping of the impacts of stakeholders' perception and interest also demonstrated the interconnectedness of the social and economic indicators (motivating factors for stakeholders' involvement in bioenergy production from the residues) and potential interactions between the stakeholders and the primary forest residues based bioenergy system.

6.2.2.9 Sectoral policies implication on sustainability of bioenergy production

Sectoral policies implication on sustainability of bioenergy production from primary forest residues was evaluated from review of the Malawi National Energy Policy, Biomass Strategy for Malawi, and Malawi Bioenergy, Food Security Roadmap, National Forestry Policy (Malawi Roadmap for Action towards Sustainable Bioenergy Development and Food Security Report, 2013; Malawi Biomass Strategy final report, 2009; Malawi National Energy Policy, 2003; Malawi National Forest Policy, 1996).

6.2.3 Key Assumptions

The following assumptions were considered in evaluating residues production and bioenergy potential of mature stand in Viphya plantations:

i) The variation in biomass between mature stands, above 25 years old, was negligible (homogenous biomass in mature stand).

ii) The difference in time efficiency η_T between AMEC and Wood-Miser mills to split logs of equal volume (equal diameter and length) into timber was negligible.

iii) Biomass to electricity conversion plant parameters: capacity factor of 0.85; overall conversion efficiency of 20% and system availability of 90%.

iv) The fossil fuels used in the supply chain undergo complete combustion.

v) Only costs and flow of materials that are directly controlled and attenuated by the bioenergy investment contribute to the cost of the residues and the bioenergy products, and the carbon footprint and embodied energy to the supply chain

6.3 Results and discussion

6.3.1 Technological impacts on stocks of mature stand, primary forest residues production and bioenergy potential

The residues generation fraction (rgf) of 0.65 and 0.45 for the AMEC and Wood-Mizer technologies respectively (Table 6.4) used for timber production in Viphya plantations, suggested that more residues are generated from the AMEC technology (269 tons/ha) than the Wood-Mizer (178 tons/ha). The difference in rgf of 0.2 between the two sawmilling technologies has the potential of creating a risk of variation in feedstock if accounting for the residues disregards the differences in quantities of residues generated when the technologies are used interchangeably. Predominant use of AMEC mills (Fig. 6.1a), which account for 80% of sawmilling technologies in the plantations, implies that more mature stands were harvested than with Wood-Mizer mills for the same demand and amount of timber.

Based on the assumption that the technologies have equal time efficiency (section 6.2.3), about 880 and 220 hectares of mature stand were harvested using AMEC and Wood-Mizer mills, respectively from an annual cut of 1100 ha, giving a total of 276012 tons of primary forest residues (Fig. 6.1c). If Wood-Mizer technology was exclusively used for timber production, 807 hectares of mature stand would have been harvested to meet the current annual timber demand, thus generating 143587 tons of residues with bioenergy potential of 2.154PJ (Fig. 6.1b). On the other hand, if AMEC was exclusively used, 1210 hectares of mature stand would have been harvested, which would generate 325672 tones with bioenergy potential of 4.9 PJ (Fig. 6.1c).

Table 6.4: Timber yield and residues generation fractions by sawmilling technology

Sawmilling technology	**Timber yield (m^3)**	**Residues generation fraction**	**Residues yield (100 tons/ha)**
AMEC (Management report)	200	0.65	2.69
Wood-Mizer (Management report)	300	0.45	1.78
Wood-Mizer LT20 (Onsite assessment)	110	0.69	1.83

The results reveal that the choice and combination of logging and sawmilling technologies in timber plantations harvested exclusively for timber production, where bioenergy production is a by-product of timber production, can have significant impact on long term availability of mature stand for timber production, flow of primary forest residues for bioenergy production and sustainability of the bioenergy systems based on the residues for feedstock. Based on the rgf values (Table 6.4), the total residues per hectare generated with AMEC milling technology from the 1100 ha of mature stand were 51% more than those of Wood-Mizer technology (Fig. 6.1a). While production of large quantities of primary forest residues by the AMEC technology can have short term positive impact of generating more energy that can be supplied to end users, the over exploitation of mature forest stands has long term negative effects on residues and bioenergy system availability, reliability and security of supply of bioenergy based on the residues supply chain. In addition, over exploitation of mature stand in the forest plantations has a negative impact on the ecosystem and the environment.

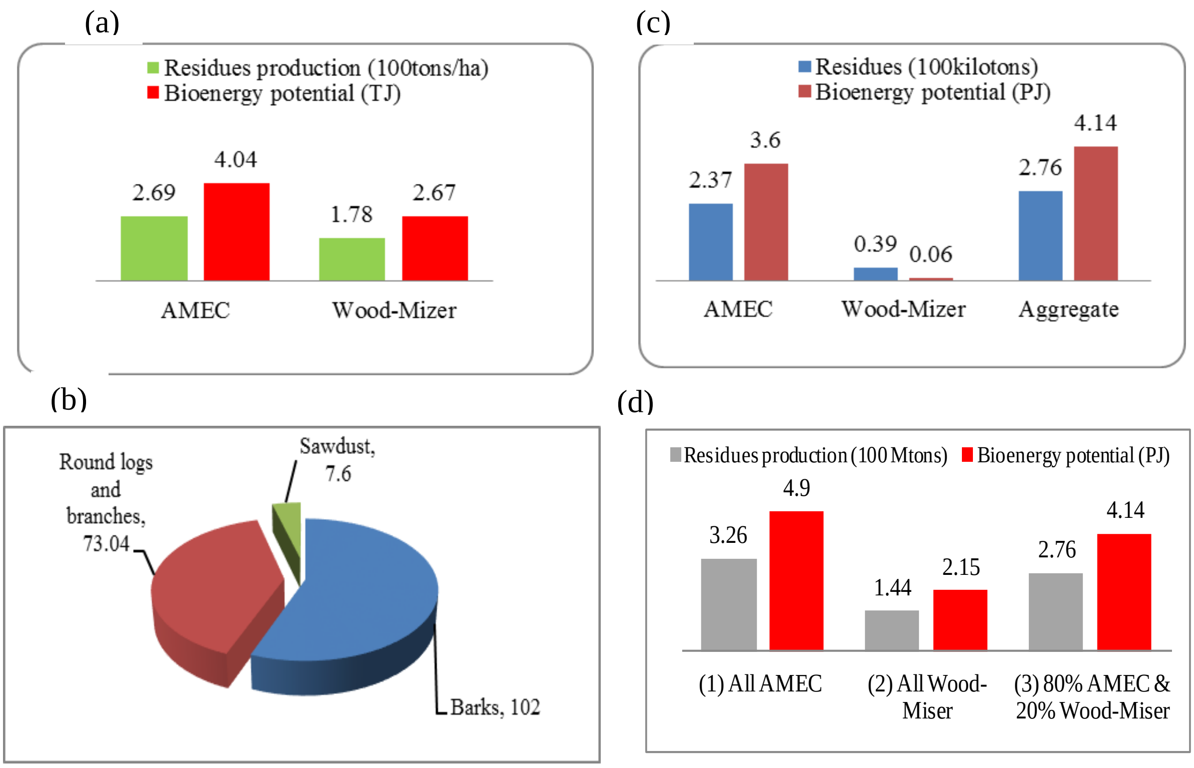


Figure 6.1: Primary forest residue (a) Total production and bioenergy potential per hectare by milling technology, (b) Production by Wood-Mizer mill from one hectare of mature stand evaluated onsite (c) Annual residues production and bioenergy potential by milling technology, (d) Production per annum and the bioenergy potential scenarios: (1) when all the equipment for milling are AMEC, (2) when all the equipment for milling are Wood-Mizer.

6.3.2 Environmental impacts

The management and harvesting systems of the Viphya forest plantations have been characterised by over extraction of mature stand, delayed replanting of harvested areas and inadequate capacity to manage forest fires. Onsite assessment of harvesting of mature stand in the plantations showed that about 2392 hectares were harvested per annum in the 14 year-period (2001 – 2014), which is about twice as much the rate of 1100 hectares per annum reported by management. Only 40% of the area harvested between 2008 and 2014 was replanted and only 65% of the replanted trees survived. Mature stand in the plantations depleted before the younger stand matured in the 25th year (Fig. 6.2a) leading to a 10 year gap with no harvesting and saw milling activities taking place.

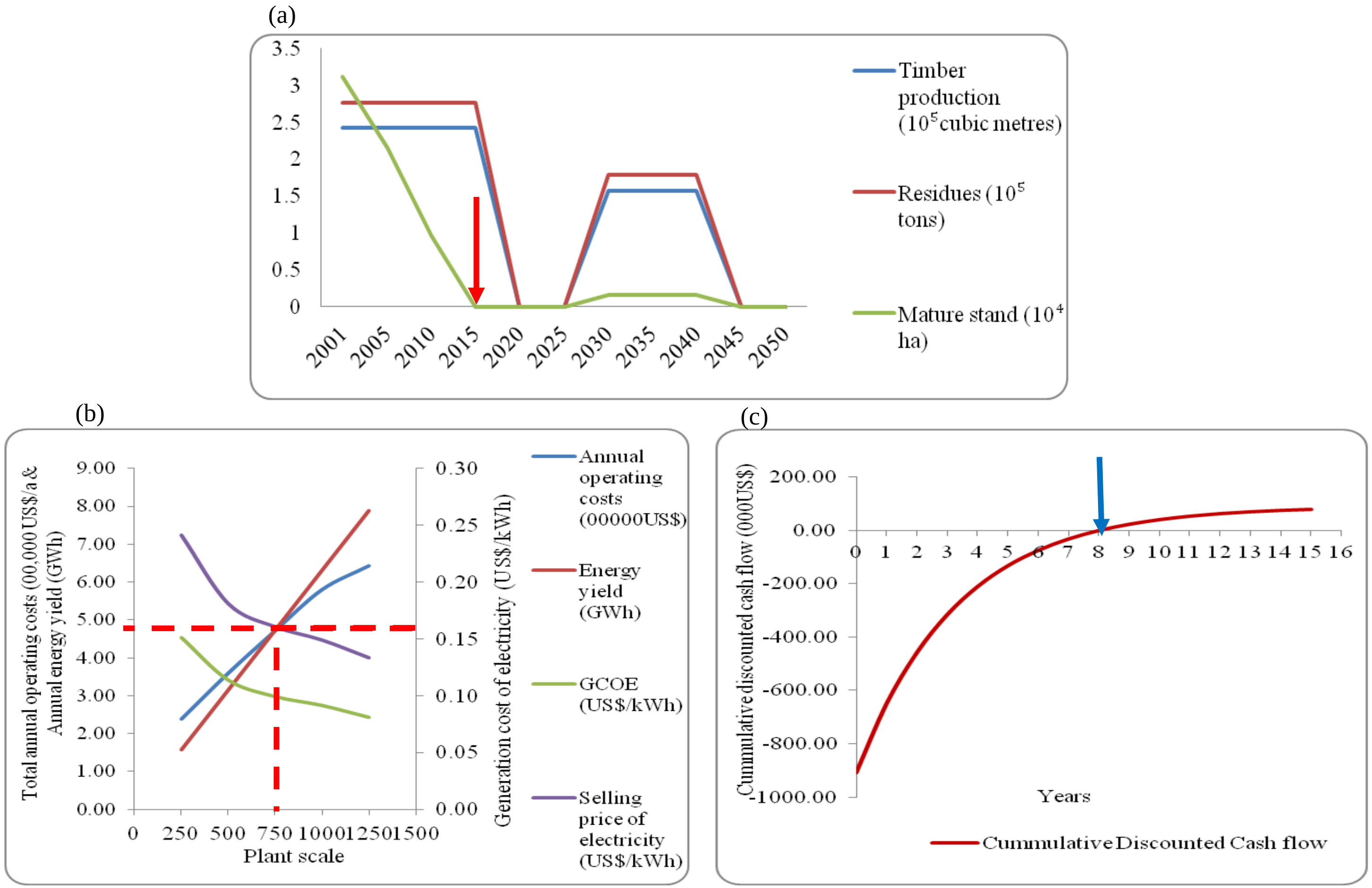


Figure 6.2: (a) Effect of over exploitation of mature stand that depletes the stocks before maturity of replanted young stand, (b) cost of generation and selling price of electricity and optimum electricity generation plant capacity evaluated from total annual operating cost and annual energy yield. In (b) the dotted lines intersect at the optimal scale and in (c) the arrow points the breakeven **point.**

Despite the potential of generating bioenergy from the residues highlighted in section 6.3.1, the management and harvesting systems in the plantations create the risk of decreasing the stocks of mature stand for timber production overtime, the amount of primary forest residues for bioenergy production in the long term and decreases the carbon sequestration potential of the plantations. Simulation of harvesting and re-planting, under the current management conditions (Fig. 6.3) indicates an increase in unsequestrated carbon over time (67.8 kilotons/annum) as a result of delayed replanting of the harvested areas.

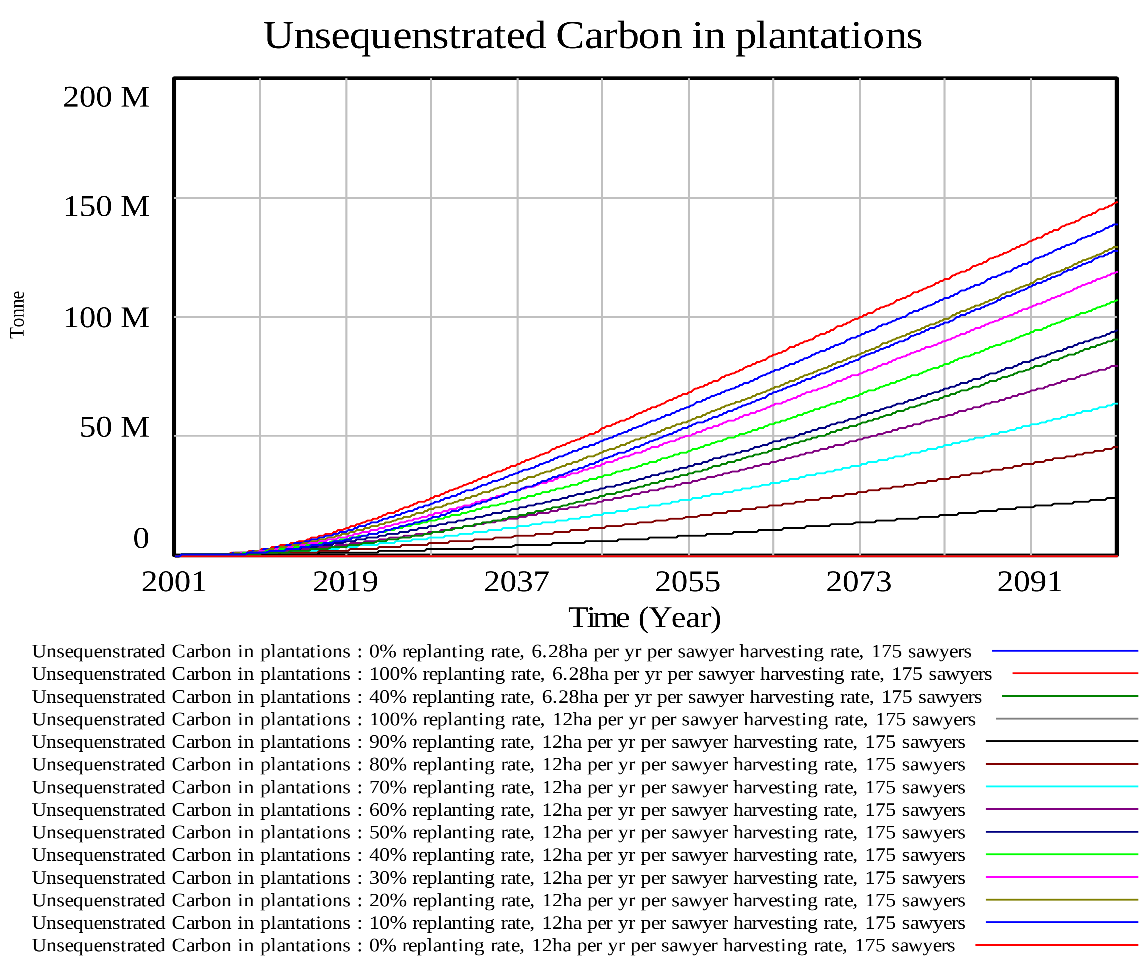


Figure 6.3: Unsequestered carbon overtime under varying annual replanting rate of the harvested areas projeted over a period of 100 years representing four cycles of harvesting and replanting in the Viphya forest plantations in northern Malawi.

On the other hand, mobilization of the residues results in carbon and energy footprints in the bioenergy value chain (Table 6.5). In the 15^{th} year, thus by the time of depletion of the mature stand in the plantations (Fig.6. 2a), about 1367 tones CO_2 would be emitted from the fossil fuels used in chainsaws and transportation vehicles and the associated embodied energy would amount to 19.5 TJ, equivalent to 0.466 kilo toe per annum (Table 6.5).

Table 6.5: Environmental, economic and social impacts of the primary forest residues supply chain in Vipha forest plantations.

Impacts	**Source (process activity)**	**Magnitude**
(1) Environmental		
Carbon footprint and embodied energy	Fossil fuels in mobilisation of the residues (On field pre-processing and transport of residues to a conversion plant yard).	1367 tonnes of CO_2 emission per annum. 19.5 TJ, equivalent to 0.466ktoe per annum
Loss of soil fertility	Removal of the residues that would have biodegraded in the plantations and add nutrients to the top soil.	Unaccounted for.
(2) Economic		
Labour costs & transport costs	Cutting branches and rejected logs, cost of fossil fuels, cost of loading and offloading onto and off the trucks, transport costs and fuel costs	US$0.182/piece of barks and logs of 5.4m long. And US$110 for clearing 1 hectare.
(3) Social		
Access to modern energy Employment Business	9.78 MW biomass to electricity system Residues mobilisation Residues transport Loss of business by the current traders in primary forest residues	80±10 communities of about 462 households, direct employment: about 27.42 man-days per hectare for residues mobilisation.

The carbon and embodied energy footprint from mobilization of the residues for bioenergy production diminish in the 10 year gap when mature stand are completely depleted. Thus, the management and harvesting systems in the Viphya plantations promote the risk of depletion of mature stand, delay the recovery of the harvested area to pre-harvest state which takes 2 to 5 years to recover after replanting (Aust & Blinn, 2004) and compromises the net carbon flow in the plantations.

6.3.3 Economic and social impacts

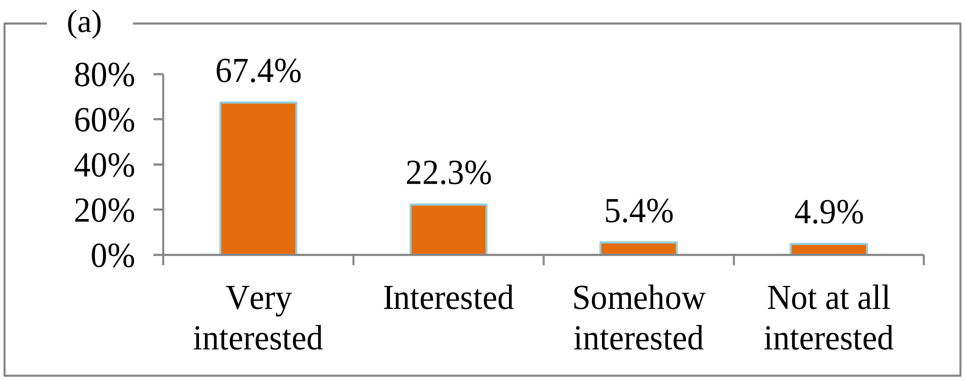
Primary forest residues annually produced in the Viphya plantations (Fig. 6.1b) can supply feedstock for 16 small scale biomass gasification systems (750 kW_E each and feedstock requirement of 12264 tons per annum) presented in Table 6.2, which cumulatively would generate 69.92 GWh per year and contribute 2.3% to the electricity generation capacity in Malawi.

A discounted cash flow of investment in electricity generation in gasification systems that would be located in a 50 km radius from the Viphya forest plantation shows that a 750 kW_E biomass gasification to electricity system would be an optimum economically viable scale at the lending rate of 35% offered by financing institutions in Malawi at the time of the study. The investment would break even after 8 years (Fig. 6.2c) at electricity selling price of US$0.16 per kilowatt-hour (Fig. 6.2b), a price that is higher than the average subsidized price of hydroelectricity in Malawi (US$0.094 per kilowatt-hour (Malawi Energy Regulatory Authority Reports 2016).

Although, the breakeven is in the 8th year, the subsequent 10 years are without any economic returns due to rapid depletion of the mature stand. Therefore, under the stated management practice, the high lending rate on capital investment would have significant impact on payback period of the investment if electricity was sold at production cost. A fiscal policy that can offset part of the cost of investment in bioenergy technologies combined with efficient forest management practices can increase the competiveness of electricity from the gasification of the residues.

Stakeholders' analysis in the primary forest residues based bioenergy production value chain revealed the power/influence and interest of key stakeholders (Table 6.2) which can influence (promote or limit) bioenergy production from the residues. About 12% of the stakeholders collect and sell the residues to urban households. These stakeholders would lose business and source of revenue hence have low level of interest in participating in bioenergy production (Fig. 6.4b). However, about 89% of the stakeholders including community leaders, sawyers, transporters, potential investors and energy regulators and policy makers show strong interest and support in prospects of modern bioenergy production but have little power (Fig 6.4b). Evidently, much of the power is with forestry management that control the harvesting and replanting of the plantations. Thus, a fragmented approach to bioenergy production between forestry and energy sectors can be the potential barriers to planning for long term supply of primary forest residues from Viphya forest plantations for electricity generation.

Social well-being as one of the sustainability indicators (Table 6.6) is the predominant motivation for stakeholders (83%) to participate in bioenergy production from the primary forest residues (Fig.6.4a). Notably, sustainability of the residues supply chain would depend on sustained interest and participation of the rural communities in the value chain as residues mobilisers and end users of the bioenergy. However, the motivation cannot be sustained with the probability of 10 years being unproductive.



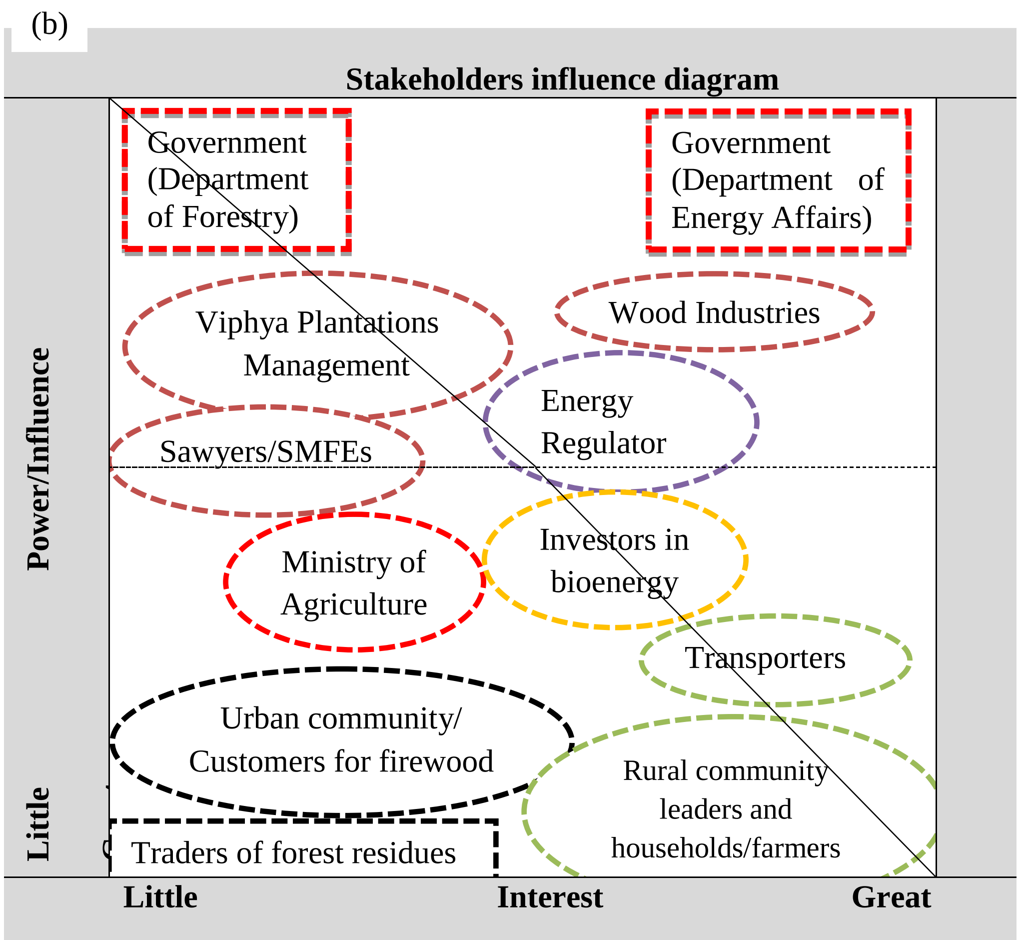


Figure 6.4: (a) Interest of stakeholders in bioenergy production from primary forest residues (%) from Viphya forest plantations and (b) Level of stakeholders' influence decision making and power and control of key policy issues in the primary forest residues-based bioenergy value chain.

Table 6.6: Key motivating factors influencing stakeholders' level of participation in bioenergy production from primary forest residues from Viphya forest plantations.

Participation frequency	**Motivating factors for participation**			
	Energy diversification	Energy for household use	Energy for business	Source of employment
Directly involved 2-3 days per week	9	26	0	1
	17 %	29.2%	0.0%	12.5%
Directly involved 4-5 days per week	8	17	1	2
	15.4%	19.1%	16.7%	25.0%
Directly involved 6-7 days per week	30	34	5	4
	57.7%	38.2%	83.3%	50.0%

The causal loop model (Fig. 6.5) developed using soft systems modelling (SSM) techniques shows the influence of the communities in the supply chain of the residues. The causal loop diagram consists of three loops: the feedstock mobilisation loop, the bioenergy production loop and the bioenergy allocation loop. The bioenergy production loop indicates that an increase in available feedstock would increase investment in the conversion plant capacity which in turn would increase bioenergy production. The increase in conversion plant capacity would need more feedstock, which would decrease available forest residues as feedstock for bioenergy production.

The bioenergy allocation loop demonstrates that the increase in bioenergy production would increase bioenergy allocation to the end users meeting the energy demand in the community which increases community perception on bioenergy to meet the energy needs. The increase in community perception would further increase community motivation and participation in feedstock mobilization which in turn increases available feedstock in the feedstock production and mobilization loop (Fig. 6.5).

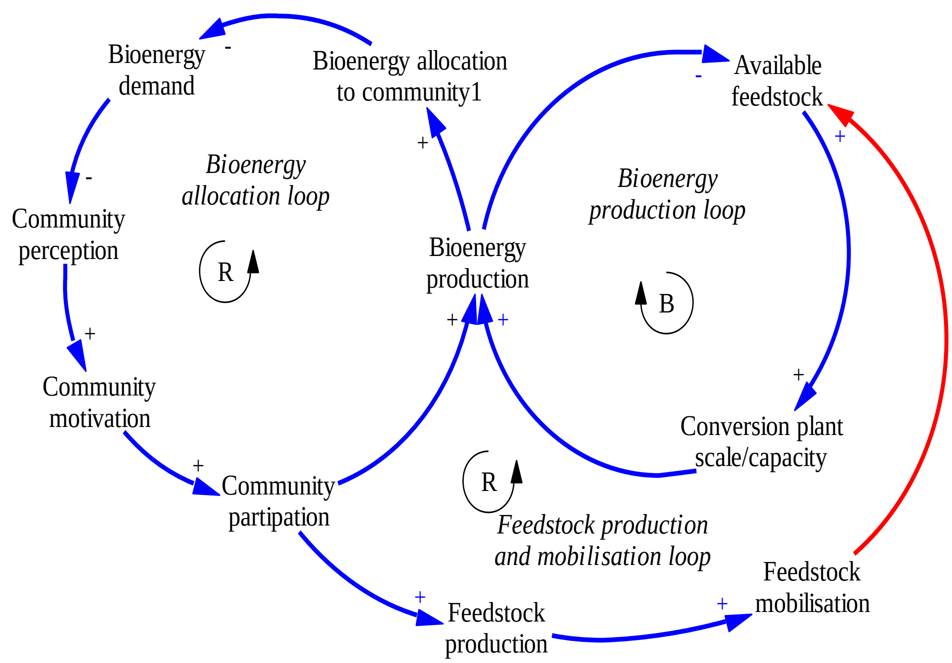


Figure 6.5: Causal loop diagram demonstrating the influence of social variables in rural communality in feedstock supply, bioenergy production and allocation to end users drawn using Vensim software.

The causal loop model demonstrates the interdependency and interconnectedness (causal-effect relationships) of the social factors in the supply chain of primary forest residues that can have impact (promote or limit) on bioenergy production from the residues. Therefore, targeted supply of the bioenergy and accrual of the benefits of primary forest residues based bioenergy system to the local communities surrounding the forest plantations can increase participation of key stakeholders in the bioenergy production value chain as feedstock mobilisers and potential market of the bioenergy products. The approach can promote development of an inclusive timber and bioenergy production systems that promote steady flow of primary forest residues overtime for bioenergy production.

6.3.4 Policy implications of primary forestry residues based bioenergy production

Although bioenergy production is supported in government policies, the fragmented approach to bioenergy development across and within policies can limit bioenergy production from primary forest residues. Bioenergy production from primary forest residues is embedded in the sectors of energy and forestry in Malawi. However, the policies and strategies in these sectors address bioenergy production and utilisation differently. The National Energy Policy, Biomass Strategy and Bioenergy Roadmap lack strategic information on bioenergy beyond firewood and charcoal (traditional biomass), size and sustainable sources of feedstock. In addition, bioenergy is excluded in the renewable energy sub sector of the energy sector [19]. The National Forestry Policy promotes biomass in form of firewood, criminalises charcoal production and lacks strategic information on sustainable sources of biomass for the rural poor households.

The fragmented approach to bioenergy is also evident from the level of influence/power of stakeholders in forest plantations management and interest in bioenergy production (Fig 6.4b). The disparity in influence and interest of the stakeholders in the forestry and energy sectors can negatively impact on planning, investment and development of bioenergy systems based on the primary forest residues for feedstock. An integrated policy framework to harmonise the sectoral policies on bioenergy production can promote sustainability of primary forest residues based bioenergy systems.

6.3.5 Whole system integration of bioenergy and timber production in forest plantations management

This study has shown that bioenergy production from forest residues from forest plantations managed and harvested exclusively for timber production, within the constraints of plantations location and scale, efficiency of harvesting technologies and maturity period of the tree species in the plantations may not be sustainable despite the bioenergy potential of the residues. Whole system integration of bioenergy and timber production as a unit system, wherein management and annual harvesting of mature stand for timber production is synchronised with annual feedstock (residues) requirement of the conversion plant over its design life span can promote sustainable production of both timber and bioenergy from primary forest residues.

Implementation of the whole system integration of bioenergy and timber production framework for management of timber plantations entails demarcation of the forest plantations into parcels for harvesting one parcel per annum (Annual Allowable Cut) to supply optimal timber demand while generating residues for feedstock requirement of optimal scale of bioenergy production plant. For instance, in the Viphya plantations where replanted trees mature after 25 years, the

33501 ha of the plantations would be demarcated in 27 annual allowable cut parcels of 1240 ha each parcel (Fig.6.6). This would enable production of about 372000 cubic metres of timber and 226424 tonnes of primary forest residues annually.

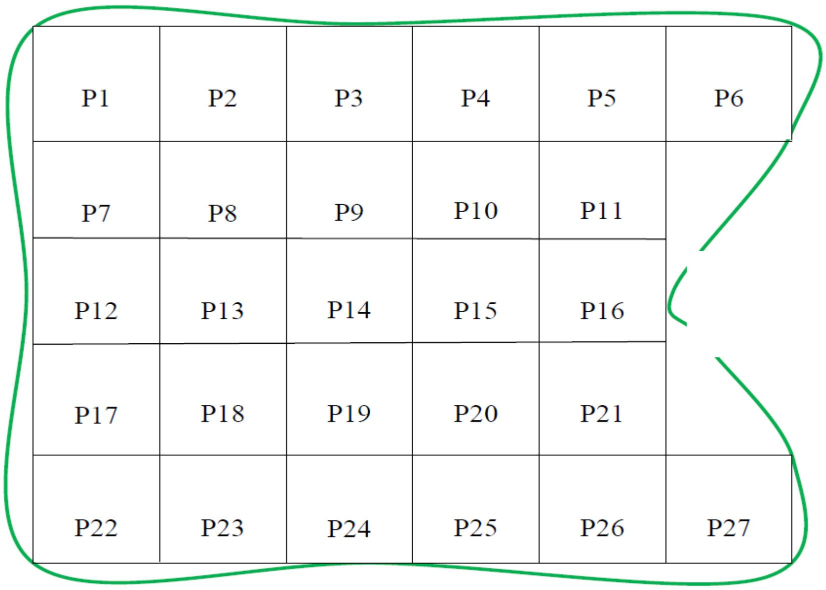


Figure 6.6: Parcels of the forest stand demarcated for annual harvesting for timber production over the maturity period of tree species in timber plantations for whole system integration of bioenergy and timber production

By synchronising harvesting and replanting cycles, replanted trees in the parcel that was harvested in first year (P1) would mature before harvesting of the last parcel in 27th year (P27). The approach would enable continuous production of timber and primary forest residues for bioenergy production (613.2 GWh per year). In addition, the approach maximises the carbon sequestration potential of the plantation by promoting constant availability of growing and maturing trees in the plantations.

6.4 Conclusion

A multi-methods approach that combines the conventional forest residues inventory, bioenergy potential and macro-economic viability evaluation of a bioenergy system with a layered five-step sustainability analysis and the soft systems modelling methods has been used in this study to assess sustainability of bioenergy production from primary forest residues. Whole system integration of bioenergy and timber production as a unit system, wherein management and annual harvesting of mature stand for timber production is synchronised with annual feedstock (residues) requirement of the bioenergy production plant over its design life span under the constraints of plantations scale, logging and sawmilling technologies and maturity age of tree species, can simultaneously support steady production of timber and bioenergy over time. Fragmented approach to bioenergy production from primary forest residues in national forestry and energy policies, regulations and frameworks can be the potential barriers to implementation of the integration of bioenergy and timber production. A policy framework for integrating bioenergy and timber production in forest plantations that accounts for local technological, environmental, social and economic constraints can promote sustainable management of forest plantations, timber and bioenergy production, economic and social benefits of bioenergy and timber, and carbon sequestration potential of the plantations. Although approached from a case study point of view, the approach used in this study can be adapted for assessing integration of individual bioenergy systems based on primary forest residues for feedstock within their specific geographic, ecological, societal, and technological context and scale, especially in developing economies where availability of reliable data is challenging.

Chapter 7: Modelling sustainability of primary forest residues-based bioenergy system

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Title: [8]**Modelling sustainability of primary forest residues-based bioenergy system**

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Objectives and summary of findings in the chapter

This chapter analyses the dynamics in primary forest residues-based bioenergy production by modelling supply chains related to primary forest residues and how these can be managed for an efficient bioresources management. The chapter addresses the work carried on objectives (ii) and (iii) of the research aimed at developing, populating and testing systems approach model for sustainable production of bioenergy, and developing an implementation strategy for sustainable production of bioenergy from primary forest residues. The chapter specifically demonstrates the dynamics in the primary forest residues based bioenergy production system emanating from management of forestry (main industry) which supply residuals to the secondary bioenergy industry.

Using system approach techniques, this chapter presents a model that demonstrates how poor management of the forestry industry (overharvesting, delayed replanting, high mortality rate of replanted trees and poor postharvest management of forest residues) makes bioenergy production and supply as the secondary industry unstable. A policy that supports integration of the two systems and avoids overharvesting is introduced, which improves all aspects of the system and and promotes stable flow of timber and bioenergy production over a projected period of 100 years. The chapter also demonstrates the impact of over harvesting and delayed replanting of

[8] *Part of this work was presented at two international and two local conferences: Bioenergy and Biofuels Conference in Sao Paulo, Brazil (29th – 31st August, 2016) as an abstract; International System Dynamics Conference, Cambridge, USA (16th – 20th July, 2017) as a poster, Annual ATTAS Conference Durban, South Africa (21st -22nd September 2016), as an abstract and at the 4th System dynamics Conference – South African Chapter, Stellenbosch, South Africa (17th – 18th November 2016) as an extended abstract,.*

harvested areas on CO_2 sequestration potential of the forest plantations over time and how this impact is improved by the policy that is introduced in the system.

7.1 Introduction

Lack of access to modern energy, such as electricity, liquid fuels and gas, limits socio-economic development in developing countries, particularly in rural areas. Primary forest residues from forest plantations, which are mostly located in the rural areas, provide renewable bioresource for production of various forms of bioenergy that can be supplied to the rural communities. These residues can be converted to generate heat, electricity, liquid transport fuels and biochemicals (IEA, 212; McKendry, 2002). However, the production of bioenergy from primary forest residues as a by-product of the timber/pulp industries (Bolkesjø et al., 2006) has the potential to present challenges to availability and security of supply of the residues to a conversion plant due to seasonality, variation of quantities and physical state. In addition, it can affect the sizing of scale of operation of the bioenergy conversion plant and the availability, reliability and energy yield of bioenergy over time. The variations over time in harvesting the mature stands for timber/pulp production are as a result of variations in demand for timber/pulp or changes in policies and practices governing management and harvesting systems and technologies in forest plantations.

In addition, the variations in production and supply of primary forest residues for bioenergy production can have significant impact on planning for investment in bioenergy conversion plant, optimum conversion plant scale and bioenergy supply to meet the energy needs of the end-users, which in turn can decrease the motivation and interest of the end-users (key stakeholders) to participate in the bioenergy value chain. Parzei et al., (2014); Eshun et al., (2010) have asserted that the harvesting methods, site characteristics, logging and sawmilling technologies and sawyers (operators) capability to operate the milling technologies influence residues generation in the wood industry. While large amounts of residues generated in the timber/pulp industries can positively influence the amount of bioenergy and biochemicals that can be produced at a conversion plant, excessive primary forest residues production per type of sawmilling technology per unit of mature stand can influence rapid depletion of stocks of mature stand in forest plantations over time, which may lead to sharp decline in stocks of primary forest residues for bioenergy production, as presented in 6.3.1 in Chapter 6. Thus, bioenergy production from primary forest residues is complex, involving many interconnected and interacting factors.

The complexity of bioenergy production is exacerbated by the interdependence, interconnectedness and the interactions of the bioenergy system with the ecological, economic social factors (Musango & Brent, 2011) and with multifaceted policy/governance frameworks (Repetto and Gills, 1988 p46) as shown in Figure 1. Forest policies are intended to affect utilisation and conservation of forest materials and are controlled by the government forest departments (Repetto and Gills, 1988). However, forest policies do not operate as standalone stratagems. Forest policies are interconnected and interact continuously with non-forest policies which have significant impact on forest use (Repetto and Gills, 1988). Sustainability of primary forest residues-based bioenergy systems is complex multifaceted governance, technical, environmental, economic and social problem. Modelling sustainability of primary forest residues based bioenergy production requires a holistic approach with inherent capabilities to reveal interrelationships and interactions (the feedback structures) at play in the system as a whole.

This study has used the system dynamics (SD) modelling methodology (Forrester, 1968; Goodman, 1974; Senge, 1990; Coyle, 1996; Sterman, 2000; Musango & Brent, 2011) to develop a model for sustainable production of bioenergy from primary forest residues using Viphya forest plantations in Malawi as a case study. The model, consisting of (1) harvesting of mature forest stand, (2) replanting of harvested area, and (3) a primary forest residues utilisation sub models, provides a better understanding of points of high leverage in the forest supply chain. The purpose is to evaluate the potential sources of variations over time (dynamics) in production and supply of primary forest residues, which can affect the availability of the forest residues for developing a sustainable bioenergy system. Specifically, the model is identifying the state-limiting processes where policy and technical innovations can promote positive and sustainable bioenergy/timber production nexus in forest plantations established and managed exclusively for the purpose of timber production. Furthermore, by using a systems thinking approach, the model is developed to evaluate the cause-effects relationships between process operations in the bioenergy systems and policies that govern the management and harvesting of the Viphya forest plantations. Therefore, identifying specific points in the value chain where either process or policy innovations or both can lead to stability in the flow of the residues to a biomass conversion plant for bioenergy production, in this case, electricity. Thus, the model can show where together, rather than singly, policy and technical innovations can lead to sustainable integration of bioenergy and timber production in forest plantations management.

The approach promotes the analysis of feedback structures that generate the dynamic behaviour intrinsic in complex social and multidisciplinary systems (Sterman, 2000; Coyle, 1996; Senge, 1990; Goodman, 1974; Forrester, 1968) such as bioenergy systems (Fig.1.1 in Chapter 1). The SD modelling methodology provides opportunity of modelling systems that adjust to changing circumstances over time (Coyle, 1996) with the objective of improving undesirable performance (behaviour or situation) of the system (Forrester, 1992). Changes in the policies that govern the forest and energy sectors and practices in the forest plantations can cause significant variations in the bioenergy production value chain.

In addition, SD modelling enables both qualitative and quantitative modelling of internally generated feedback processes and time delays involved in the dynamic behaviour throughout the whole system networks. Therefore, the approach provides opportunity to model qualitative social variables of power/influence, interest, motivation and willingness to pay for energy services of key stakeholders in the value chain. In addition, it enables detection of points in the system where effected small change can result in significant change in system behaviour (points of high leverage) and development of efficient policies/management strategies necessary for the stability of the system (Bleijenbergh, 2016; Park et al., 2014) . Furthermore, assessment of feedback processes and time delays in the forest residue and bioenergy networks leads to identification of potential sources of intermittent production supply of the residues and variations in bioenergy production over time. Overall, the model would help in identifying the potential enablers and disenablers to sustainability of the integrated timber and bioenergy production systems.

7.1.1 Overview of Malawi energy sector and potential for forest residues-based bioenergy production

Provision of sustainable energy, especially to the rural and semi urban households, is one of the main challenges facing development of the energy sector in Malawi. Only 1% and 35% of the rural and the urban proportions of the population respectively have access to grid electricity. Thus, about 98% of the rural and semi urban households in Malawi rely on traditional biomass in the form of firewood and charcoal for all the energy needs (Zalengera et al., 2014; Kaunda, 2012; Openshaw, 2010). Fuelwood is collected from indigenous forests and is unsustainably burnt in inefficient cook stoves (Openshaw, 2010). However, despite the challenges besting the biomass sub-sector of the energy sector in Malawi, other bioresources such as primary forest residues from forest plantations are poorly managed and underutilised.

Significant quantities of primary forest residues are produced from logging and sawmilling processes in Viphya forest plantations (Figure 1.2 in Chapter 1), which form the largest single block of forest plantations in Malawi (Ngulube & Chirwa, 2012; Kafakoma & Mataya, 2009). The plantations established in the 1960s, cover 560 km^2 consisting of 53501 hectares (ha) of mainly pine trees (*Pinus patula and Pinus kesiya*). Since the establishment, the plantations were not harvested until 2001 after which over 90% of the mature forest stands have been harvested over a period of 15 years with partial replanting of 40% of the harvested area per annum (Kafakoma & Mataya 2009). Therefore, most of the Viphya forest plantations are still in the first cycle for timber production with trees that are less than 25 years (maturity age) since re-plantation started.

About 20 000 hectares of the plantations are managed and harvested by private wood industry (RAIPLY) through concessionary agreement with the Government of Malawi (GoM). The GoM through the Department of Forestry (DoF) manages about 33501 ha where plots of mature stand are sold to small and medium forest enterprises (SMFEs) (Kafakoma & Mataya, 2009). The plots of mature stand allocated to SMFEs are harvested by clear-cut method in which all the trees on a site being harvested are cut down and processed into timber within the plantations. The sawyers use semi-automatic AMEC (AMECCO, China) and Wood-Mizer (Wood-Mizer, LLC, USA) sawmilling technologies, which have efficiencies of 35% and 55%, respectively.

Primary forest residues consisting of rejected round logs, barks, branches, sawdust and stumps produced from the logging and sawmilling processes are left in the plantations. Every year, about 65% of the residues are destroyed by wildfires during hot summer (Chitawo & Chimphango, 2017, unpublished) and the remainder are collected for competing uses (materials for construction and firewood) in peri-urban areas.

Primary forest residues produced in Viphya forest plantations can be utilised for production of modern forms of energy (bioenergy) such as electricity in decentralised small-scale gasification systems with capacity of 250 kW_E to 1200 kW_E (Chitawo & Chimphango, 2017, unpublished). The model developed in this study provides strategic information for informed decision making at policy and investment levels for the development of sustainable bioenergy systems utilising the residues for feedstock.

Targeted supply of bioenergy from primary forest residues to the low income rural communities around the plantations can increase participation of the communities in management of the plantations while accessing the benefits of the bioenergy project that are mostly leaked to urban areas in centralised grid connected bioenergy systems. The paper underscores holistic assessment of sustainability of residues-based bioenergy systems, as a whole system property (Goh et al., 2010) covering process operations and policies in the primary systems that generate the residues and bioenergy production and supply to end use processes.

7. 2 Materials and methods

System dynamics modelling methodology has been used to model the Viphya forest residues based bioenergy system. Figures 7.1(a) and (b) show the framework, system boundary and the steps (Forrester, 1992) followed in developing the model. The model building process is outlined in Figure 7.2. Data used for populating the model was collected from stakeholders from forestry, energy, transport and agriculture sectors and from rural community households living in the peripheral of the plantations in a survey conducted in Malawi. Table 7.1 presents the categories and numbers of the stakeholders that participated in the survey.

Participants from the forestry, energy, transport, and agriculture sectors were selectively identified based on ranks in the sectors, profession, resource ownership, involvement in forestry residues value chain, and formulation and implementation of energy and forestry policies and regulations, using non-probability sampling approach. Participants from the household category of stakeholders from a rural community were randomly selected from the registers of Village Heads using random numbers generated in excel.

Table 7.1 Categories of stakeholders in field survey

Stakeholders	**No.**
Policy makers (Energy, Forestry, Agriculture)	10
Sawyers	29
Rural community households around the forest plantations	98
Transporters	16
Traditional leaders	7
Civil Society Organisations	2
Merchants (timber and forest residues traders/sellers)	22
Total	184

A combination of semi structured and structured questionnaires and group discussions was used to collect data from the stakeholders to determine power and influence in the management of the Viphya plantation on timber throughput, harvesting technologies and residues generation fractions was obtained from plantations management reports and from interviews with the sawyers. The sample questionnaires have been provided in supplementary materials (S1).

Data on timber throughput, harvesting technologies and residues generation fractions was obtained from plantations management reports and from interviews with the sawyers. Onsite inventory was done on one hectare of freshly harvested mature stand, using Wood-Miser sawmilling technology, to validate the data obtained from plantations management reports. Statistical Package for Social Scientists (SPSS) and Microsoft Excel were used to analyse the data.

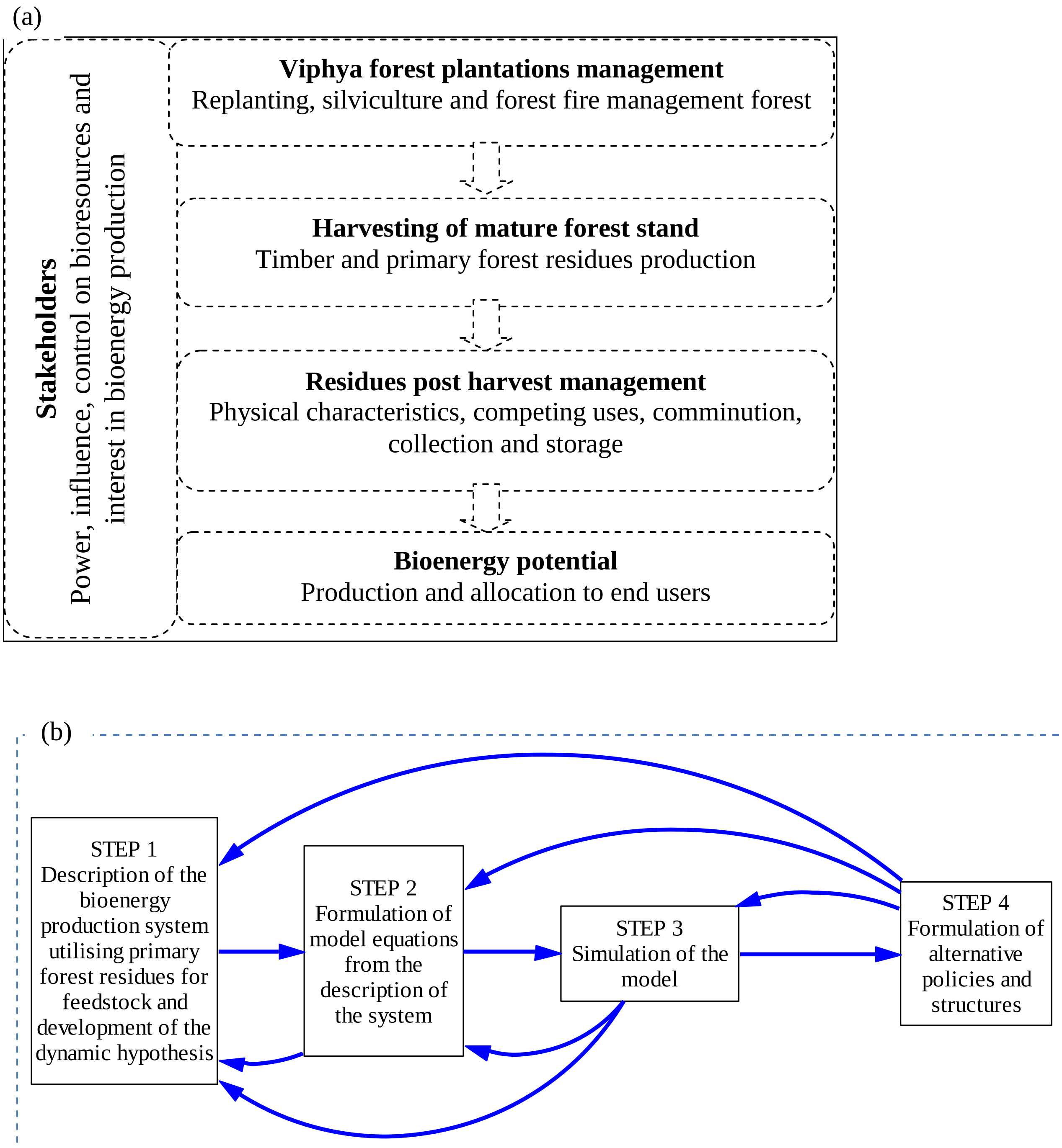

Figure 7.1: (a) Modelling framework and model boundary for primary forest residues supply chain from Viphya forest plantations (b) Key steps in system dynamics modelling of the bioenergy production system (adopted from Forrester, 1992).

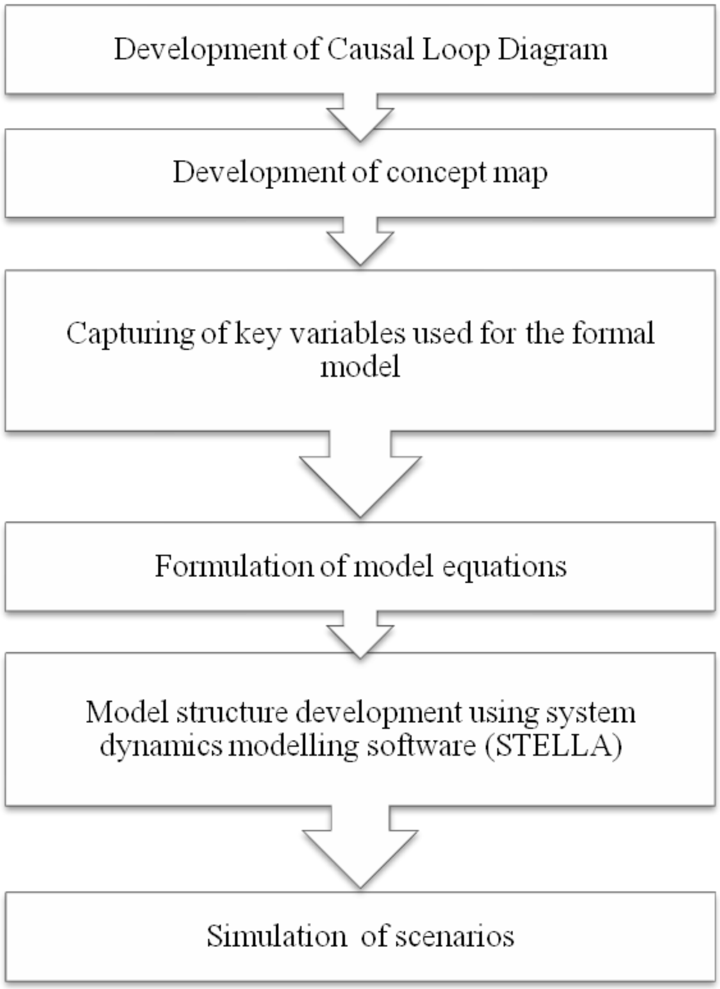

Figure 7.2: The model building process expanded from steps 2 and 3 of Figure 1b

7. 2 Eliciting system structure information from stakeholders

A dynamic hypothesis (step 1 in Fig. 7.1b) was developed to provide a description of a working theory (Morecroft, 2015; Oliva, 2003) of the bioenergy system utilising primary forest residues from Viphya forest plantations in Malawi. Qualitative data collected from stakeholders in the primary forest residues value chain, in the survey conducted in Malawi, was correlated and aggregated into key concepts using the framework suggested by Flick et al., (2014 p57). The key concepts drawn from the data and the links between concepts are given in the cognitive map in Figure 7.3 drawn in vensim system dynamics modelling software. The cognitive map was used for eliciting system structures, interrelationships between structures and development of causal-loop diagrams to identify feedback loops that reveal potential sources of variations in the forest residues-based bioenergy value chain. The key variables and the interrelationships between sets of variables deduced from the cognitive map have been presented in the causal loop diagrams in Figure 4.

The survey revealed that harvesting of mature stand in the Viphya forest plantations over a period of 14 years (2001 -2014) had been characterised by over exploitation of mature stand as a result of high demand for timber, overly use of inefficient sawmilling technologies and encroachment of mature stand in the forest driven by the socio-economic state of communities around the plantations. In addition, inadequate investment in plantations management decreased the capacity to control forest fires, monitor the sawyers when harvesting mature stand and to replant the area harvested by the sawyers.

Onsite assessment of the management and harvesting systems in the plantations exhibited the lack of a harvesting and replanting plan of mature stand and the harvested areas which could have sustained the stocks of mature stand over time. Only 40% of the area harvested between 2008 and 2014 had been replanted by 2015. Under investment in the forest plantations management decreased the capacity to monitor and control forest fires which increased the death fraction of replanted young stand (0.35 per year). In addition, about 700 to 1500 ha of the plantations were destroyed by forest fires during dry and hot summer annually, which increased replanting requirement in the plantations. Pine tree species (*Pinus patula and Pinus kesiya*) predominant in Viphya plantations mature after 25 years. Thus, delayed and partial replanting of the harvested area and the area destroyed by forest fires in the plantations has negative impact on stocks of mature stand for timber and primary forest residues supply chains over time relative to the maturity time of the tree species.

Furthermore, onsite inventory of primary forest residues production per annum showed the dependency of mature stand harvested per year on the number of sawyers operating in the plantations, the harvesting rate per sawyer and the residues generation fractions of the sawmilling technologies used for timber production. Hand chainsaws and Wood-Mizer and AMEC milling technologies are used for logging and sawmilling.

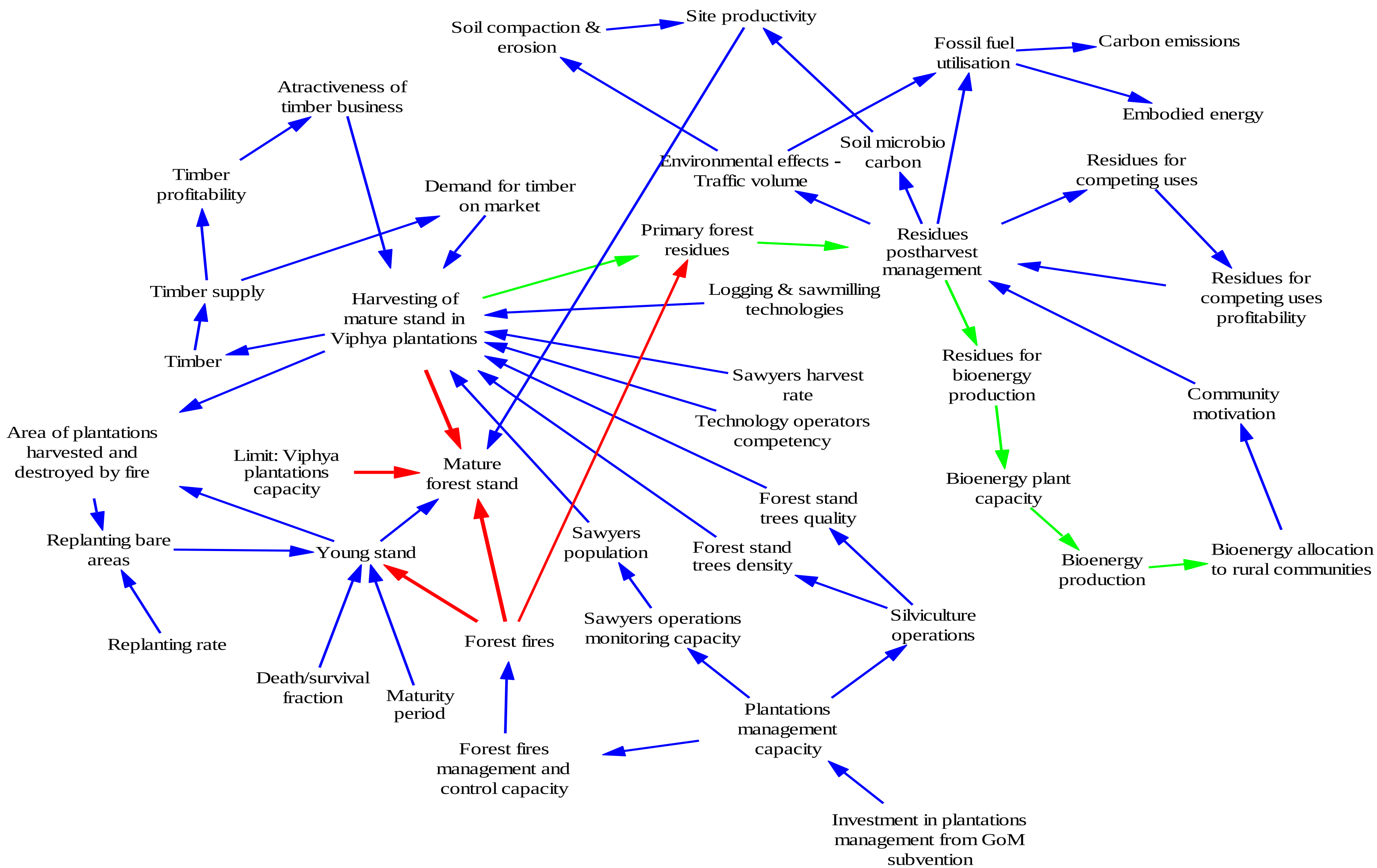

Figure 7.3: Cognitive map model of Bioenergy system based on primary forest residues from Viphya forest plantations showing the conceptual views from replanting to bioenergy allocation.

We obtained the proportion of residues per unit volume of standard log sawn into timber generated by each type of the sawmilling technologies (residues generation fractions) of 0.45 and 0.65 for Wood-Miser and AMEC respectively. About 80% of the sawmilling technologies were AMEC and 20% were Wood-Miser mills. Residues yield of 182.6 and 269 tonnes per hectare for Wood-Miser and AMEC mills respectively, and the effect of excessive use of AMEC (less efficient) mills on long term availability of mature stand in the Viphya forest plantations have been evaluated (Chitawo & Chimphango, 2017, unpublished). AMEC technology felled more mature stand than Wood-Miser mills for supplying the same amount of timber, which in turn increased the depletion rate of mature stand in the plantations.

The dynamics in primary forest residues for bioenergy production are exacerbated by significant proportion of the residues that are collected for competing use. Annually, about 35% of the residues (barks and rejected round logs) are collected by the merchants and sold to urban and semi urban households as firewood and materials for construction, which in turn reduce the amount of the residues that can be collected for bioenergy production. Introduction of primary forest residues based bioenergy production in the plantations would create competition for the residues in the supply chain with these stakeholders that collect and sale the residues. The policies/practices/decisions in management and harvesting systems in Viphya plantations and postharvest management of the residues promote the variations in stocks of mature and immature stand, and the amount of primary forest residues that can be recovered from the plantations for bioenergy production

The inventory of mature stand showed that only 4000 ha were available in the 33501 ha-section of the Viphya forest plantations managed by the government, by the first quarter of 2015. The results reveal that on average about 2100 ha had been harvested per annum in the 14 years (between 2001 and 2014). However, Plantations management reported the annual harvesting rate of 1100 ha which suggests unaccounted for harvesting in the Viphya plantations. Stakeholders' analysis revealed that about 65 to 84% of the stakeholders identified the demand for timber and profitability of the timber business as motivating factors for harvesting mature stand in the plantations.

The causal loop diagrams in Figure 4 were developed as a precursor to quantitative simulation model of the bioenergy system utilising primary forest residues from Viphya plantations in Malawi. The loops present and elucidate the relationships between variables and feedback structures in the system. The loops also provide understanding of the consequences emanating from the information in policies and practices in management and harvesting of the Viphya forest plantations.

The causal loop diagrams consist of eight loops: the harvesting loop B1, the replanting loop R1, the primary forest residues production loop B2, the residues utilisation loops R2 and B3, the bioenergy production loop B4, the bioenergy investment loops B5 and B6 and the bioenergy profitability R3. The harvesting loop B1 shows that an increase in harvesting of mature stand decreases net mature stand in the plantations and, over time, the decreases in net mature stand decreases harvesting of mature stand. Therefore, harvesting of mature stand impacts negatively on net stock of mature stand, which over time, impacts negatively on harvesting of the mature stand. The impact can be substantial if the mature stands in the plantation are overly exploited.

The replanting loop R1 shows that increase in harvesting of mature stand increases the area harvested in the plantations which increases the requirement for replanting. After a delay, replanting of the harvested area increases stocks of young stand that increases maturing stand, which in turn increases the net mature stand after maturity time of 25 years for the predominant pine tree species that are planted in the plantations. The increase in netmature stand increases harvesting of the mature stand over time thus, signifying a reinforcing loop denoted R1. However, partial replanting which was at 40% of the harvested area at the time of this study, negates restocking the plantations for steady availability of mature stand.

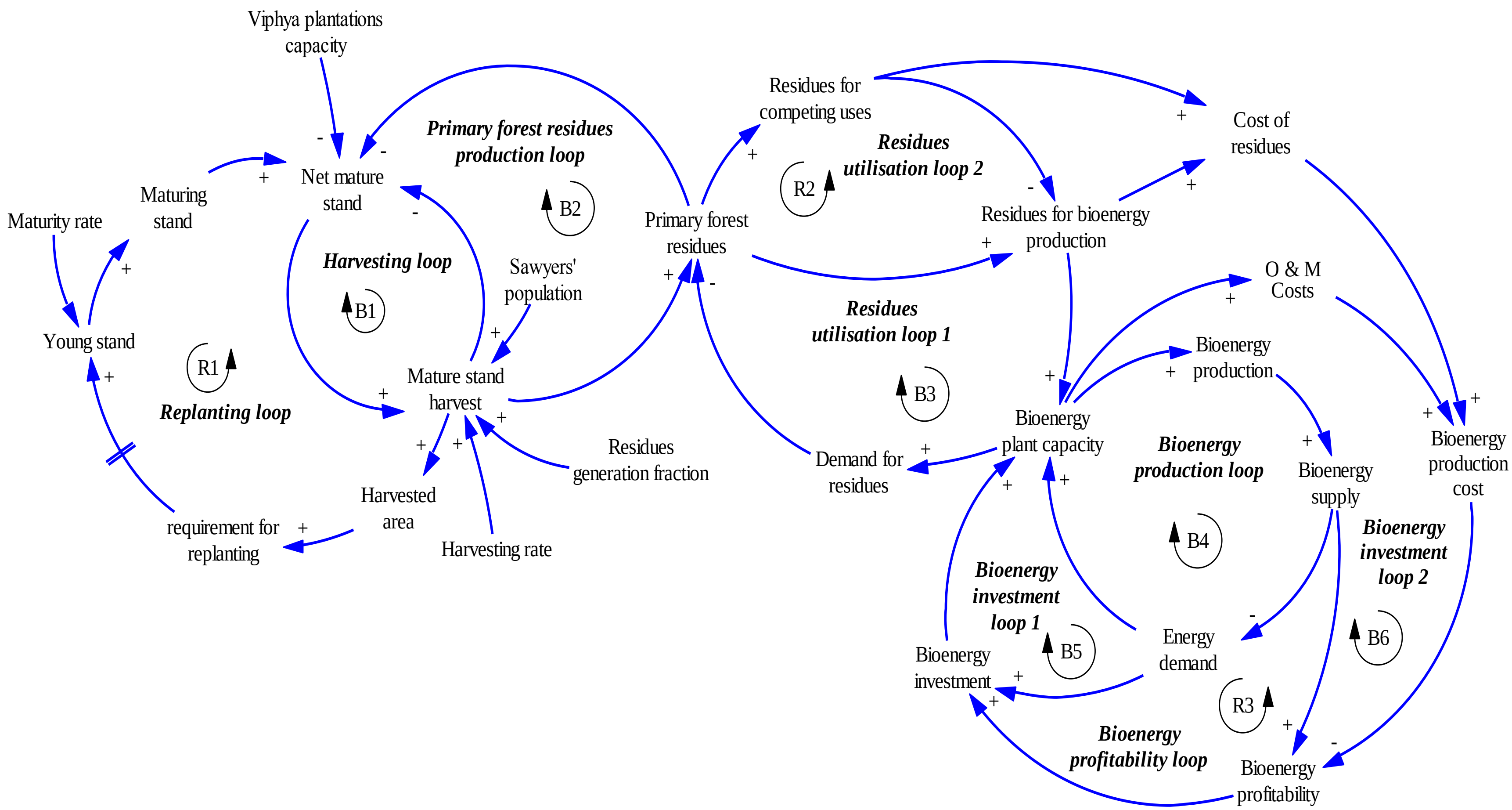

Figure 7.4: Causal loop diagram for the primary forest residues based bioenergy production system showing the interconnectedness and relationships of variables from replanting of the plantations to bioenergy allocation to end users.

The primary forest residues production loop B2 indicates that an increase in harvesting of mature stand increases primary forest residues produced in the plantations. More residues are produced when AMEC sawmilling equipment with efficiency of 35% is used than when Wood-Mizer equipment with efficiency of 55% is used to supply the same amount of timber. Thus, the increased use of AMEC technologies over produces the primary forest residues, which decreases the net stock of mature stand in the forest plantations. Consequently, both timber and primary forest residues production decreases over time.

The residues utilisation loop consists of reinforcing loop R2 and balancing loop B3. Loop R2 indicates that an increase in residues production increases residues collected for competing uses which decreases the residues that would be available for bioenergy production. The decrease in the residues that would be available for bioenergy production decreases the bioenergy plant capacity that can be sustainably supplied with the primary forest residues for bioenergy production. The decrease in the bioenergy plant capacity decreases the demand for the primary forest residues which in turn increases residues accumulation in the plantations over time.

The loop B3 shows that an increase in residues production increases residues for bioenergy production which increases the bioenergy plant capacity that increases the demand for the primary forest residues. The increase in demand for primary forest residues decreases primary forest residues accumulation in the plantation. The decreases in residues accumulation would decrease the residues for competing uses. Therefore, introduction of bioenergy creates competition for residues between bioenergy production and the other uses which can be modeled as escalation archetype in system dynamics.

The bioenergy production loop (B4) indicates that an increase in bioenergy plant capacity increases bioenergy production that increases energy supply to end use services, which in turn decreases the energy demand. The decrease in energy demand decreases bioenergy plant capacity. The bioenergy investment loop 1 (B5) shows that an increase in energy demand increases investment in bioenergy production that increases the bioenergy plant capacity. The increase in bioenergy plant capacity increases bioenergy production that increases bioenergy supply, which in turn decreases the energy demand. The decrease in energy demand decreases bioenergy investment that decreases bioenergy plant capacity over time thus, giving a balanced loop.

The bioenergy investment loop 2 (B6) indicates that an increase in bioenergy plant capacity increases operation and maintenance costs which increase bioenergy production cost that decreases bioenergy profitability which in turn decreases investment in bioenergy production. The decrease in bioenergy investment decreases bioenergy plant capacity over time. The interactions and the feedback structures in the bioenergy systems presented in the causal loop diagrams have the potential to cause variations over time in bioenergy production and supply to end use processes.

Steady availability and supply of primary forest residues, to a conversion plant of optimal capacity to meet the energy needs of the end users, is critical for sustainability of the system. Therefore, maintaining steady availability of mature stand for timber and primary forest residues production in the replanting and harvesting loops and keeping the competition for the residues at constant in the residues utilisation loops are vital points for improving the performance of the bioenergy system.

7. 2.1 Model equations

The main parameters in systems approach modelling are stocks (materials or resources that accumulate or deplete over time), flows (the rates at which the stocks accumulate or deplete) and the constants (values that influence the flows). Model equations (Step 2 of Figure 3b) for the stocks and flows were formulated and have been presented in Chapter 4

7.2.2 Stocks and flows model simulation

The stocks and flows simulation model structure given in Figure 7.5 was developed using [9]STELLA (isee systems) system dynamics modelling software that aids simulation of complex nonlinear systems to demonstrate the state of the system variables that accumulate or decrease over time (stocks), how the variables are changing (flows) and the factors (constants) influencing the changes (Coyle, 1996). The model consists of five key stocks: mature forest stand, area harvested, primary forest residues, bioenergy and carbon not sequestered. Table 7.2 shows the flows or each stock. Replanting increases the mature stand after a delay of 25 years (maturity period). Thus, the sub model for the forest stand was cascaded into five stocks of immature forest stand to capture the delay.

[9] STELLA stands for Structural Thinking, Experimental Learning Laboratory with Animation. It is a system dynamics modelling software developed and licensed by isee systems: https: https://www.iseesystems.com/

Modelling and simulation of sustainability of primary forest residues-based bioenergy system enabled predicting the future flow of primary forest residues for bioenergy production resulting from alterations in process or operational policy in the forest plantations and the primary forest residues value chain. The model equations have been provided in 4.2.3 in Chapter 4.

Table 7.2: Key stocks and flows in the model

Stock	inflows	outflows
Mature stand	replanting	harvesting
Area harvested	harvesting	replanting
Primary forest residues	harvesting	residues collection for bioenergy & residues collection for competing uses
Electrical energy (bioenergy)	bioenergy production	bioenergy supply
Carbon not sequestered	carbon sequestration	

Three scenarios were formulated for simulation of the model. The business as usual (BAU) scenario represents the existing condition of high death fraction (0.35), replanting rate of 40% of the harvested area per year and sawyers productivity of 12 ha per year in the plantations. The annual allowable cut (AAC) scenario was obtained by varying the replanting rate incrementally between zero and 1, the death fraction decrementally between 0.35 and 0 and the harvesting rate incrementally between 6.23 ha reported by management and 12 ha obtained on site from the sawyers. The model was simulated in 10 runs for a time horizon of 100 years from 2000 to 2100. The runs and scenarios have been presented in Table 7.3 and Table 7.4, respectively.

Table 7.3 Scenarios for simulation of the SD Model

Scenario (SimRun)	Replanting rate (%)	Death fraction of young stand (Mortality)	Harvesting rate per sawyer per annum (ha/year) (Sawyer productivity)	Number of sawyers on site (Sawyer staff size)
1	0% (Extreme condition)	0.35	12	175
2	40% (BAU)[10]	0.35	12	175
3	100%	0.35	12	175
4	100%	0.2	12	175
5	100%	0.1	12	175
6	100%	0.0	12	175
7	100% (AAC 1)[2]	0.1	7	175
8	100%(AAC 2)	0.05	7	175
9	100%(AAC 3)	0.0	7	175
10	40%	0.35	7	175

[10] BAU (Business As Usual) scenario representing the existing management regime in the Viphya forest plantations

[2] AAC = Annual allowable cut

Table 7.4: Scenarios for simulation of forest stand dynamics, primary forest residues and bioenergy production

Simulation run	**Scenario**
Run 1	Control run of zero replanting of harvested sites at 12 ha per sawyer per year sawyers productivity and 0.35 tree mortality fraction
Run 2	Maintain the status quo of over exploitation of mature forest stands (12 ha per sawyer per annum) and low investment in forest plantations management that leads to high death rate of replanted trees, lack of capacity to monitor and control forest fires, and inadequate monitoring of sawyers activities in harvesting mature stand in the plantations. This is presented as Business As Usual (BAU) scenario.
Runs 3 to 5	Increase replanting fraction of the harvested area and death (mortality) fraction of trees in the plantations.
Runs 7 to 9	Implement an optimum harvesting rate (annual allowable cut) of 7 ha of mature stand per sawyer per year, synchronise harvesting and replanting by replanting 100% of the harvested sites of the forest and reduce mortality fraction of the trees. This is referred to as annual allowable cut (AAC) scenario.
Run 10	Control run of 40% replanting rate at 7 ha per sawyer per year for the 175 sawyers that operated in the plantations and mortality fraction of 0.35 of replanted trees.

7.3 Results and discussion

7.3.1 Quantitative model of the forestry-bioenergy system

The stock and flow diagram (Fig. 7.5) was developed based on the notion of capturing the essential processes at play in the forest plantations management and bioenergy systems from replanting of the harvested sites in the forest to bioenergy production. The model captures the physical essence of stand dynamics and is a simplification of the causal loop diagram, starting with an initial stock of mature stand of 33501 ha which are harvested annually for timber production. The rate of harvesting per year (an outflow) depends on the number of sawyers (sawyer staff size) operating in the plantations and the productivity of each sawyer. The number of hectares harvested by each sawyer per year, which is referred to as productivity of the sawyers in the model, depends on availability of mature stand. At the same time, harvesting of the mature stand decreases the mature stand in the plantations. Trees replanted in the harvested sites mature (maturing as an inflow) in the 25th year (transition time) after replanting. The amount of replanted stand that attain maturity after 25 years is affected by mortality of the replanted trees, which was estimated at 0.35 in consultation with the Viphya forest plantations management. The rate of change of mature stand in the plantations is the sum of initial stock of mature stand and maturing less harvesting given by equation 7.1.

$$\frac{dMS}{dt} = MS_{in} + m_s - h_s \qquad (7.1)$$

Where:

$\frac{dMS}{dt}$ is the change in mature stand in the plantations in time dt.

MS_{in} is intitial mature stand (ha)

m_s is maturing stand (ha/year)

h_s is harvesting (ha/year)

In the first 25 years, there are no maturing stands. Therefore, $m_s = 0$, and the sawyers harvest the initial stock of mature stand. Immature stand are cascaded in five levels with the age difference of five years. Therefore, the key stocks in the forest management stocks and flows sub model structure are the mature stand and immature stand while as the key flows are harvesting, replanting and maturing. The effects of delayed replanting of the harvested sites and overharvesting of mature stands have been highlighted in the dynamic hypothesis and in the causal loop diagram (Fig. 7.4).

We compared the existing scenario of over exploitation of mature stand and partial replanting, presented as business as usual (BAU) in Figure 7.6a, and a new policy that limits harvesting of mature stand to a specific number of hectares per annum, referred as annual allowable cut (AAC) (Fig 7.6b – 7.7d). In the new policy, harvesting of mature stand is moderated and limited to 1240 ha per year while replanting 100% of the harvested area and limiting mortality rate of the replanted trees to <1%.

Results from a quantitative stocks and flows model (Fig. 7.5) simulated over a time horizon of 100 years (4 complete cycles of '*Replanting-Maturity-Harvesting*' of trees in the forest plantations demonstrate the dynamics in mature stand, primary forest residues production, bioenergy production and carbon sequestration potential over time. The results in Figure 7.6 and Figure 7.7 show the impact of harvesting of mature stand, partial replanting of harvested area and mortality rate of replanted trees on bioenergy production and carbon sequestration over time. Over exploitation of mature stand at 2100 ha per year (12 ha per sawyer per year for 175 sawyers) and partial replanting (40% of the harvested area) in the BAU (business as usual) scenario in Figure 7.6, and Figure 7.7, result in sharp decrease in mature stand over time (Fig. 7.6a).

Similarly, availability of primary forest residues (BAU in Fig. 7.6d) decreases owing to the direct correlation between timber and primary forest residues production from mature forest stand. Thus, long term availability of primary forest residues for bioenergy production is undermined in the over-exploitation case prevailing in the plantations. More residues were produced in the first 15 years before mature stand were completely depleted which resulted in a 10 year-gap (Fig. 7.6a), of timber and primary forest production before maturity of the first stock of replanted trees. Results from simulation of the stock and flow model of 12 scenarios (Table 7.3) show that mature stand in the plantations decrease over time at partial replanting of the harvested area, high death fraction of the replanted young stand and harvesting rate of 12 ha per sawyer per year (Fig. 7.6b BAU scenario).

In addition, partial and delayed replanting of the harvested area and high death rate leave some land out of the system over time, which decreases the potential recovery of the harvested sites to pre-harvest status and compromises the carbon sequestration potential of the plantations (Fig. 7.7d). It can be observed in Figure 7.7d that carbon that is not sequestrated increases over time as a result of partial, delayed replanting and high death fraction (0.35) of young stand being replanted each year. Therefore, under investment in the management capacity of the Viphya plantations compromises environmental opportunity cost of carbon sequestration by the young and maturing stand.

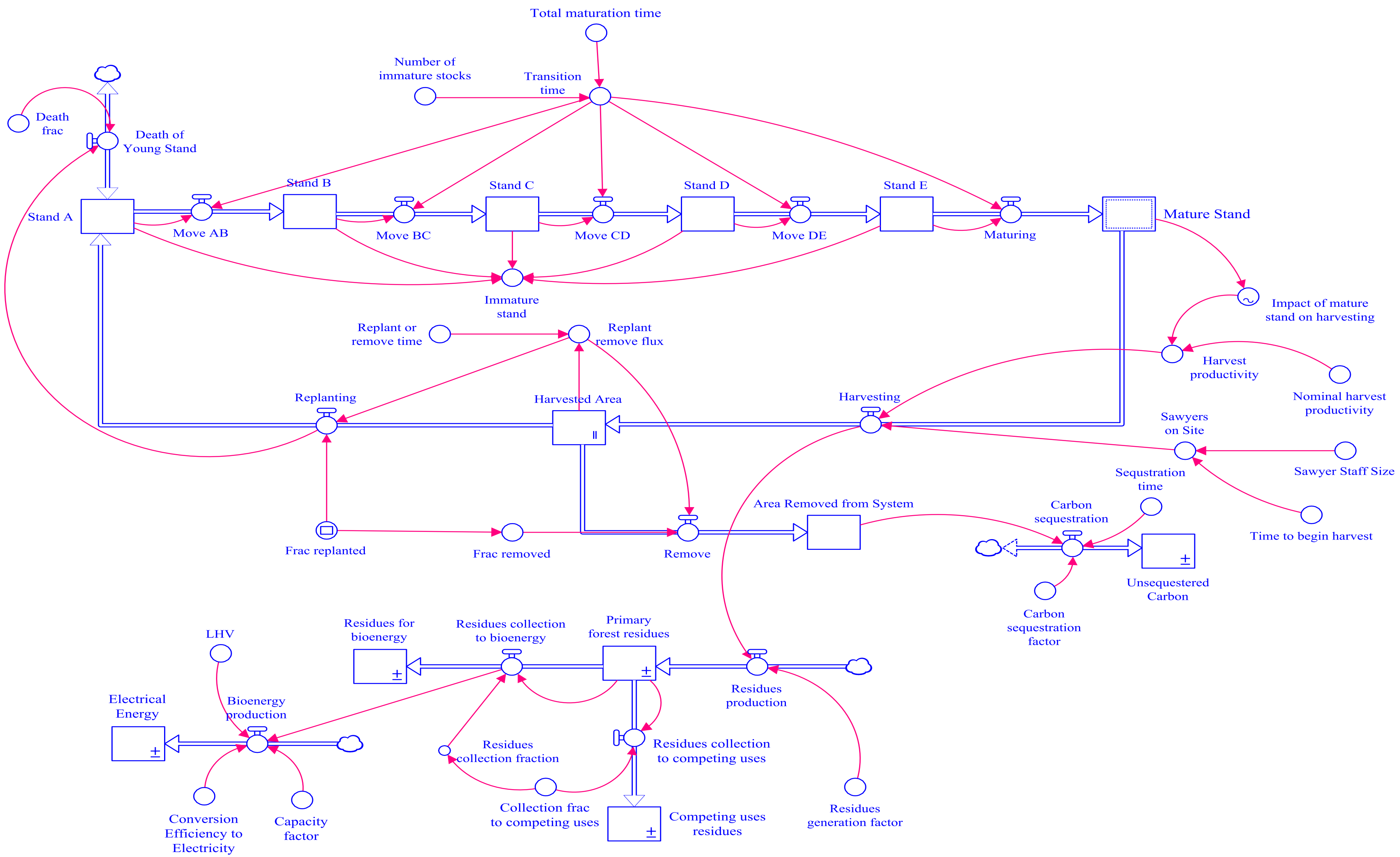

Figure 7.5: Stock and flow diagram of the bioenergy system based on primary forest residues from Viphya forest plantations in Malawi.

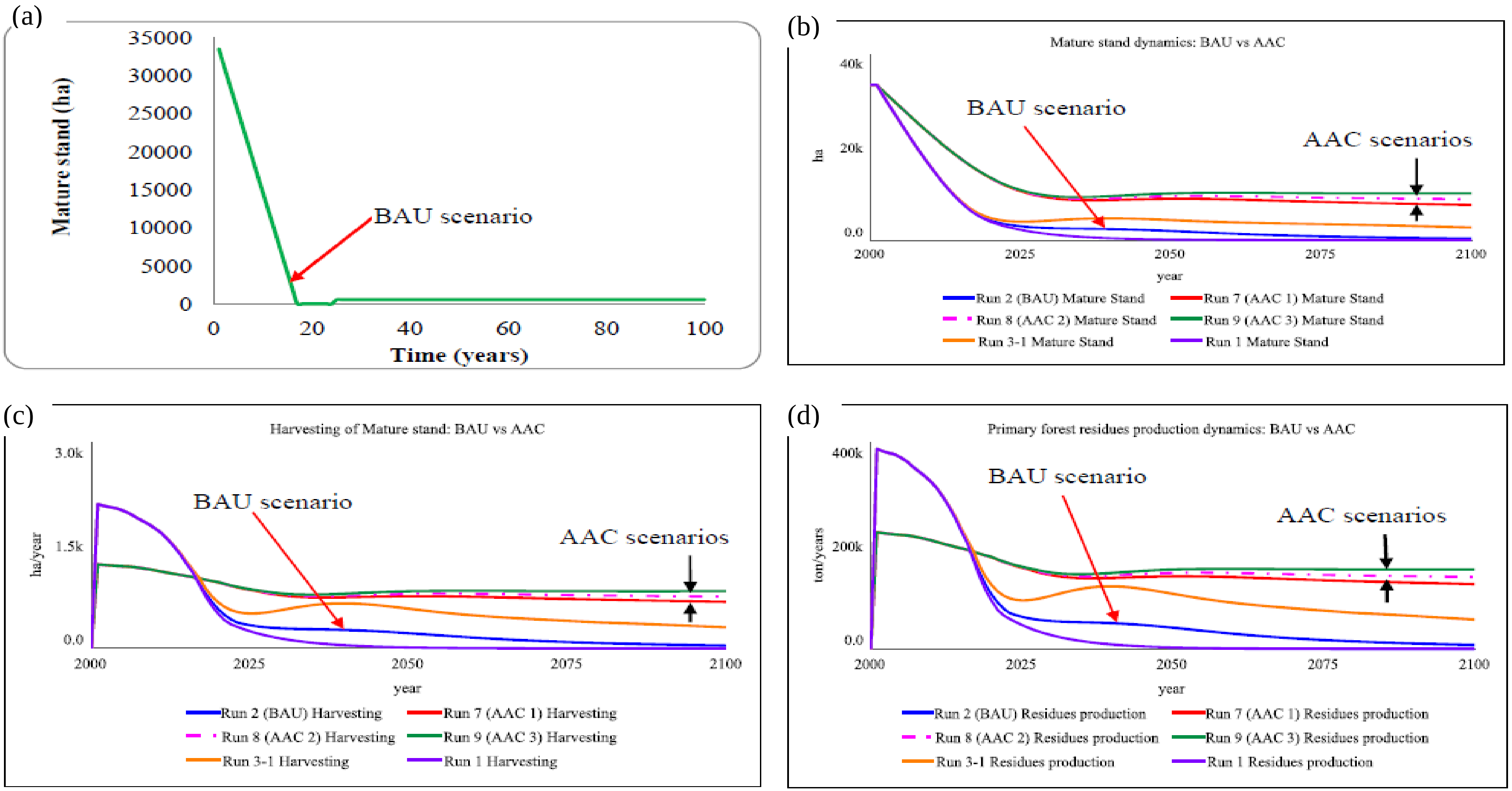

Figure 7. 6: (a) Mature stand at 2100 ha/annum harvesting rate, 40% per annum replanting of harvested area and 0.35 death fraction of replanted trees plotted in excel: Business as usual (BAU) case; (b) Mature stand for BAU and Annual allowable cu (AAC) scenario (c) harvesting, (d) residues production simulated over a time horizon of 100 years using STELLA Architect software at scenarios 0% to 100% replanting rate, 1240 and 2100 ha annual harvesting rates, 0.0 to 0.35 death fraction of replanted trees.

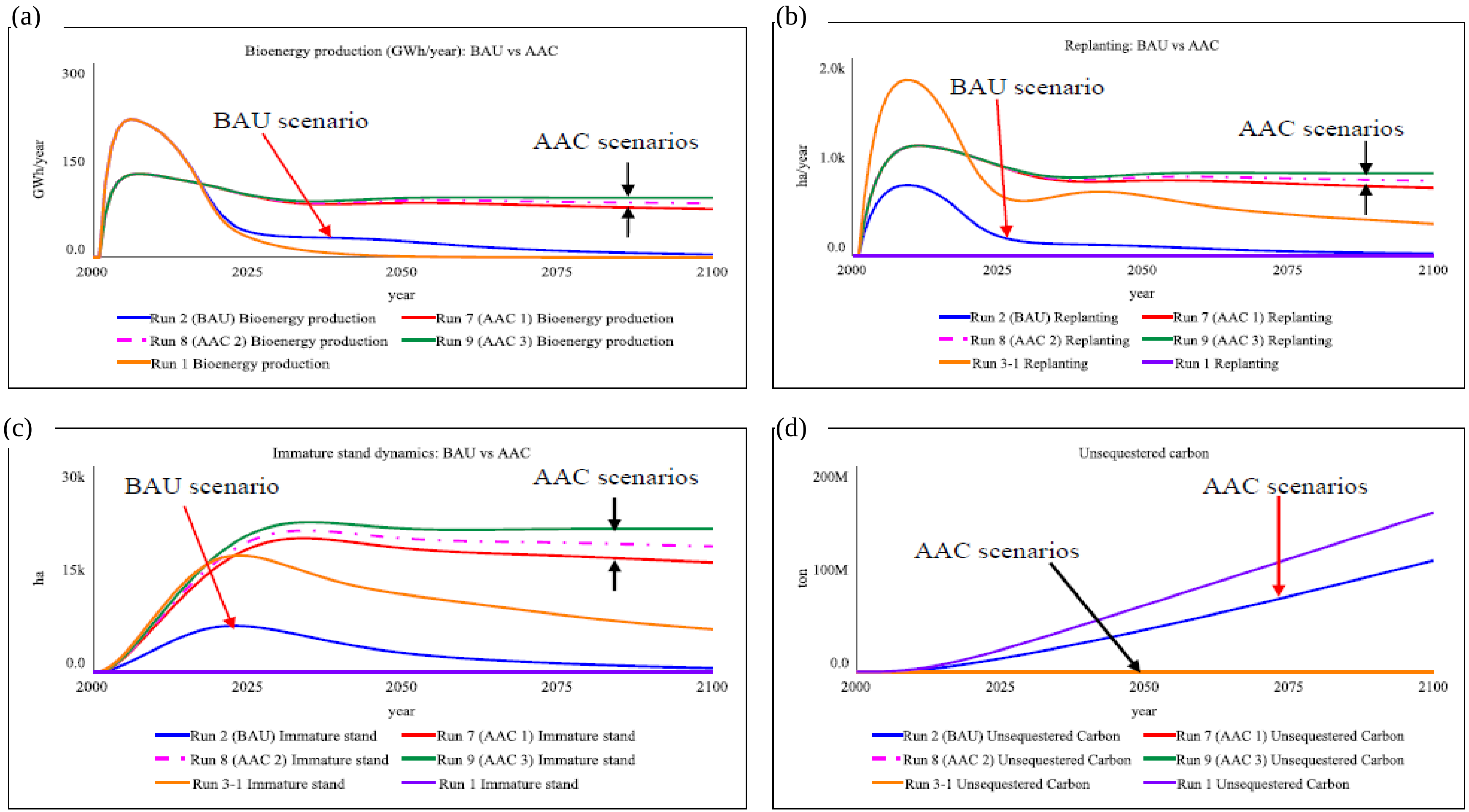

Figure 7.7: Dynamics in primary forest residues-based bioenergy value chain: (a) bioenergy production, (b) replanting of harvested areas in the forest plantations, (c) maturing and (d) Loss of carbon sequestration potential in the Viphya forest plantations simulated over a time horizon of 100 years using STELLA Architect software at scenarios 0% to 100% replanting rate, 1240 and 2100 ha annual harvesting rates, 0.0 to 0.35 death fraction of replanted trees.

An integrated bioenergy and timber production framework (Chitawo and Chimphango, unpublished) was introduced in the model (AAC scenario) to improve the performance of the systems. The framework entails demarcation of the forest plantations into parcels for harvesting one parcel per annum (Annual Allowable Cut) to supply optimal timber demand while generating residues for feedstock requirement of optimal plant scale of the bioenergy production system. Furthermore, in the framework, each sawyer is allowed to harvest 7 ha of mature stand per annum, management capacity is improved through reinvestment in plantations management capacity to replant 100% of the area harvested each year and reduce the death fraction of the replanted young stand to ≤ 0.1.

The results of the AAC scenario (Fig.7.6b, c and d) show constant availability of mature stand for harvesting for timber production that promotes stable flow of primary forest residues and bioenergy production. Equation 7.2 shows the model equation for replanting of a minimum area (MRA) of the plantations that is equal to an annual allowable cut (AAC) plus area of dead young stand.

$$MRA = AAC + ADS \tag{7.2}$$

Where:

MRA is minimum replanted area,

AAC is annual allowable cut of mature stand for timber production

ADS is area of dead replanted young stand in the plantations

In addition, the AAC scenario promotes constant forest cover of mature, maturing and immature stand (Figure 9b and 10c) of about 95%, which in turn promote ecosystem balance and carbon sequestration potential in the growing stocks of the forest plantations.

7.4 Conclusion

Variations in primary forest residues supply chain from forest plantations, which are exclusively managed for timber/pulp production, can have significant impact on availability and reliability of bioenergy production systems based on the residues for feedstock and on bioenergy allocation to end use processes. The sources of these variations at individual forest plantations within the context of specific socio-economic and technological environment need to be understood in order to promote resilience in the feedstock supply chain and sustainable bioenergy systems. Forest plantations stand management is critical to steady flow of residues. In particular, rapid depletion of stocks of mature stand that leads to variations in primary forest residues and bioenergy production is critical setback to the development of sustainable bioenergy systems in plantations that are poorly managed. Carbon sequestration potential is compromised by partial and delayed replanting of the harvested area in the plantations.

Technologically, over use of inefficient technologies promotes rapid depletion of mature stand in the forest plantations. Estimation and implementations of annual allowable cuts (AAC) of the mature stand and replanting the total area harvested and area of dead young stand per annum can promote steady flow and reliability of both timber and primary forest residues, and bioenergy production and supply to end use processes. Specific site policy and technical innovations may vary from plantation to plantation based on the power/influence and interest of key stakeholders which may influence the type and level of innovations. Steady availability of mature stand that can be harvested for timber production is a key sustainability indicator of the bioenergy system utilising forest residues for feedstock.

This paper contributes strategic information for decision making at forest and bioenergy policy and investment levels on development of integrated bioenergy production and forest management systems. The approach promotes resilience of timber plantations as sources of feedstock for bioenergy production, and how the whole system can simultaneously promote sustainable bioenergy and timber production, and ecosystem management and carbon sequestration by promoting constant availability of about 95 percent of forest cover over time. Thus, the paper contributes to the debate of intensive and sustainable forest plantations management as source of renewable and sustainable energy, by promoting effective and holistic integration of bioenergy production and forest plantations management systems.

Chapter 8: A synergetic integration of bioenergy and rice production in rice farms

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Title: [11]**A synergetic integration of bioenergy and rice production in rice farms**

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Objectives and summary of findings in the chapter

This chapter presents the work carried on objectives (i) and (iii) of the research, particularly on rice straws and husks supply chain. The quantities and bioenergy potential of rice straws and husks, viable conversion route and scale of the conversion plant to generate electricity for supplying state-limiting operations in low-income rice farming communities are presented in this chapter.

The annual throughput of rice straws and husks from the rice farms is sufficient for generation of 16.64 GWh of electricity. Targeted supply of electricity generated from the residues to irrigation water pumping, can increase rice production and availability of rice residues for bioenergy production. Therefore, an innovative synergetic integration of rice and bioenergy production can promote sustainable production of rice residues-based bioenergy.

8.1 Introduction

Irrigation pumping is an energy limiting productive unit operation in rice farming in Karonga district in northern Malawi. The lack of energy in the agricultural sector in the district that can be used for irrigation, has confined irrigated rice production to rice schemes with gravity-fed irrigation systems (Malawi Biomass Strategy final report, 2009; Energy Demand Assessment Report, 2011; Malawi Roadmap for Action towards Sustainable Bioenergy Development and Food Security Report, 2013). Synergetic integration of bioenergy and rice (food crop) production in rural rice farming communities presents the

[11] Part of this work was presented at an Internal Bioenergy Conference in Manchester, United Kingdom (22[nd]-23[rd] March, 2017), as a poster.

opportunity to simultaneously meet energy and food demands without requiring extra land resources.

Rice is one of the four main staple food crops grown in Malawi, after maize (corn), cassava and potatoes. Significant quantities of rice straws and husks are produced annually in rice farms and processing mills but they are economically underutilised (Zalengera et al., 2014). The straws and husks can be converted to other forms of energy, besides burning to supply modern forms of energy such as electricity [Lim et al., 2012; Hiloidhari & Baruah, 2011; Suramaythangkoor & Gheewala, 2010; Gadde et al., 2009). In most rice producing regions, some of the straws and husks are used by the households for cooking and water heating (Hiloidhari & Baruah, 2011; Iye & Bilsborrow, 2013; IEA, 2012 p222; Scarlat et al., 2011; IEA, 2010 P343; IPCC, 2011), while large proportions are burnt in open fires in the field as part of land clearing and preparation for next planting season (Shafie et al., 2014) or at the rice processing plants as a means of disposal. Therefore, the energy contained in the straws and husks is wasted when the straws and husks are burnt in the open fires. Bioenergy from the straws and husks could provide potential substitute for fossil fuels that is required to power irrigation pumps and other unit operations in rice production.

Fossil fuels have intensively been used in rice production for powering upstream as well as downstream processes, thus, cultivation, agro processing, packaging and transport to markets (Bardi, et al., 2015) but have remained the central component and a limiting factor of agricultural productivity in developing economies. The volatility of the global market of fossil fuels negatively affects the security, availability and reliability of fuel supply in countries like Malawi that largely depend on imported petroleum products. Over dependence on fossil fuels in crop production has resulted in high carbon footprint per unit mass of the crops, variations in costs of crop production overtime and food prices as a result of the frequent variations in fossil fuel prices (Jianyi et al., 2015; Xu et al., 2013; Nazlioglu et al., 2013; Nazlioglu & Soytas, 2012; Nazlioglu, 2011).

On-site production of electricity at the farms that can be supplied to crop production provides potential alternative clean and sustainable source of energy (McKendry, 2002), which can be reliable and affordable compared to fossil diesel and electricity from the main grid. In case of rice production, the electricity generated from biomass can contribute to reducing carbon footprint per unit mass of rice and offset the cost of fossil fuels and grid electricity. As a result, holding other factors constant, rice production is likely to increase, thus enhancing food security. The extent to which on-site electricity production can increase rice production, and reduce greenhouse gas emissions overtime and the cost implications on the associated unit operations and the economics of the farming, has not been assessed.

The rice straws and husks that are left at the farming site and rice processing plants, respectively, go through a gradual biodegradation process that releases methane (CH_4) into the atmosphere. Methane is 21 times more potent greenhouse gas than carbon dioxide (CO_2) (IPCC, 1996). Therefore, bioenergy production from the straws and husks has the potential to reduce the methane gas emissions besides contributing to a secure energy supply (Shafie et al., 2014).

Previous studies have reported on potential conversion routes that allow production of diverse forms of energy (Zalengera et al., 2014; Lim et al., 2012) or intermediary energy carriers and co products from rice straws and husks. For example, the physical and chemical characteristics of rice straws and husks (Suramaythangkoor & Gheewala, 2010) provide the opportunity to convert them to heat and electricity in a cogeneration mode or only heat or electricity in a single form of energy generation mode (Shafie et al., 2014; McKendry, 2002; Sims, 2002 p143,168; Hiloidhari & Baruah, 2011; Suramaythangkoor & Gheewala,.2008). Rice straws and husks can be converted to bio char, bio oils and product gas through pyrolysis and gasification (Islam et al., 2011; Ji-lu, 2007; Kapur et al., 1996). The high content of cellulose and hemicelluloses in the rice straws provides opportunity for conversion of rice straws and husks through biochemical processes of hydrolytic to fermentable sugars for production of bioethanol (Lim et al., 2012; Nagalakshmi, 2011; Swain &, Krishnan, 2015; Binod et al., 2010; Khaleghian et al., 2015). The volatile matter and the fixed carbon in rice husks can be converted to biogas in anaerobic digestion (Okeh et al., 2014; Kalra & Panwar, 1986; Zhang & Zhang, 1999). The biogas could be used for cooking in gas stoves or for generation of electricity in spark ignition engines coupled to generators (McKendry, 2002b).

Viable technology configurations for conversion of rice residues to electricity have been reported in Thailand (Suramaythangkoor & Gheewala, 2010; Delivand et al., 2011), Malaysia (Shafie et al., 2013), India (Chauhan, 2012) and Brazil (Chaves et al., 2016), which include: direct combustion (boiler → steam-turbine → generator) and gasification (gasifier → gas turbine → generator or gasifier → internal combustion engine). Electricity generation using downdraft biomass gasifiers, coupled with internal combustion engines, have shown favourable economies of scale of low capital cost per kilowatt-hour, unlike the biomass → boiler → steam turbine → generator configuration (Raman & Ram, 2013; Buragohain et al., 2010). The downdraft gasifiers provide producer gas which has relatively low tar content with acceptable quality for use in internal combustion engines (ICE) for generation of electrify (Chaves et al., 2016). The restriction on scaling up downdraft gasifiers to a maximum plant capacity of 250 kW (Raman & Ram, 2013) provides opportunity for deploying small-scale modular systems in the rice farms in rural areas suffering the lack of electricity.

Rural electrification based on agricultural residues is evidently not a new phenomenon (Suramaythangkoor & Gheewala., 2010; Suramaythangkoor & Gheewala,.2008). However, the implementation strategy of such bioenergy systems is not effective in promoting sustainable integration with food systems. Consequently, rural communities are expected to access the biomass generated electricity through the main electricity grid where they have very little control and participation. Therefore, the system is characterised by several loopholes that leak benefits directed to the communities. Furthermore, the benefits from the conventional rural electrification programmes to the rural communities are improperly accounted for by considering the number of connected communities rather than what the electricity was used for and the actual impact it made on their livelihoods.

This study has developed a systems approach closed-loop process for integrated bioenergy and rice production system promoted by introduction of on-farm self-generated bioenergy for powering irrigation pumping on rice farms during off season. A case study of rice farms in Karonga district (Fig. 1.2b) in the northern part of Malawi, based on a10-year historical rice production data, is used to demonstrate how bioenergy generation (electricity) from rice straw and husks, if targeted to a specific energy limiting productive unit operation in rice production, can be used as an enabler for promoting positive fuel /food nexus. In this approach, the electricity generated from the rice straws and husks using a small-scale downdraft gasifier coupled with internal combustion engine (ICE) rated 250 kW_E, with capacity factor of 0.8, is specifically applied to power water pumps for irrigation of the rice farms during dry season. The potential of such targeted bioenergy system to promote positive integration with food production with regard to food security, feedstock availability, financial returns and greenhouse gas emissions savings has been assessed. In the base year, the bioenergy generated from the rice straws and husks is initially used to power irrigation pumps to irrigate part of the rice farms during the dry season. The increase in rice yields increases the availability of rice straws and husk as bioenergy feedstocks for the subsequent cycle. As the bioenergy production capacity increases, the portion of land that is irrigated during off season increases correspondingly.

The approach is considered holistic and strategic for allowing the rural communities to benefit from direct use of biomass generated electricity where it would make the most positive impact in their livelihood. In addition, the partial implementation of the off season irrigation allows communities to gradually adapt to the increase in rice production which might necessitates increasing capacity of downstream operations. The increase in capacity of the downstream operations can be strengthened by the resilience of the rice straws and husks supply chain overtime. The assessment of the potential for carbon and financial savings and revenue generated from increased rice production, when bioenergy from rice straws and husks is supplied to rice production, is done using fossil diesel and/ or conventional grid electricity as benchmarks.

8.2 Materials and methods

Data collection involved a field survey undertaken in Malawi with the stakeholders in agriculture (national and division levels), energy and the rural households in rice farms in Karonga district. Data collected using structured and semi structured questionnaires, formal group discussions and from literature captured historical rice production trends in a 10 year period and projected over a 15-year period.

8.2.1 Assessment of rice straws and husks production

Rice straws and husks produced in rice farms in Karonga district have been obtained from the10-year (2005 to 2014) historical data on rice production obtained from Ministry of Agriculture in Malawi. The quantities of rice straws and husks generated per annum have been estimated using residues to product ratios reported in literature (Jiang et al., 2012; Okello et al., 2013; Hoogwijk et al., 2003; Rossillo-Calle et al., 2007). The annual production of rice straws and husks have been using equation (8.1) reported by Rossillo-Calle et al.,(2007).

$$R_{CR} = (C \; x \; RPR) \tag{8.1}$$

Where:

R_{CR} is the annual production of crop residues;

C is the annual rice production; and

RPR is the residues to product ratio of rice straws or husks

As a result of unrecorded data on the farms and at the government offices, the proportions of residues collected for competing uses to bioenergy, were estimated through interviews with the stakeholders and experts in the agriculture sector and the rice farmers. Bioenergy potential from the rice straws and husks was estimated using equation (8.2) and the heating value (HV) reported in (Okeh et al., 2014; Binod et al., 2010; Kalra & Panwar, 1986), which were validated in an experiment using the Standard Test Method for Gross Calorific Value (ASTM Standard D5865-11A. 2011). Table 8.1 shows the residues to product ratios and the heating values reported in literature and the heating value of husks obtained in the experiment that was used in this study.

$$Q_{ER} = (RR_T \times LHV) \tag{8.2}$$

Where:

Q_{ER} is the bioenergy potential of the residues in MJ

RR_T is total rice residues collected from the rice farms and mills in tonnes

LHV is lower heating value of the residues in MJ/kg

8.2.2 Electricity generation from rice straws and husks

Electricity generation from the rice straws and husks for supplying power for irrigation pumping in the rice farms and meeting other energy needs of the rural rice farming communities, has been simulated in a small-scale decentralised system using downdraft gasifier with feeding rate of 400 – 500 kg/h that is coupled with GTA 1710G Cummins engines rated at 250 kW_E, with net power output of 200 kW_E and efficiency of 24.5% (Table 8.2) for a projected period of 15 years. The cyclic production of rice, rice straws and husks and bioenergy has been done based on material balance (including irrigation land balance) and energy balance.

Table 8.1: Residues to product ratio and heating values of straws and husks

	From literature		From experiment
	Residues to product ratio [43-46]	Heating values (MJ/kg)	Heating values (MJ/kg)
Rice straws	1.757, 1.0:1.4 [46]	8.83 [39], 14.7 at 20% mc [46],	-
Rice husks	0.267, 1.0:1.4 [46]	12.9 [39], 14.7 at 20% mc [46]	13.2 at 8% mc

8.2.3 Cost benefit analysis and profitability evaluation

Profitability of electricity generation from rice straws and husks in a downdraft gasifier has been evaluated using the discounted cash flow criteria (Turton, 2013) and parameters given in Table 8.2. The financial gains from the use of the bioenergy have been estimated from the difference between the cost of fossil diesel for running the water pumps for irrigation of the rice farms and the cost of bioenergy, which includes labour and transport costs for collection and transportation of the rice straws and husks to a conversion plant.

The financial gains from using bioenergy have been estimated from the cost of fossil diesel that would have been used to run the water pumps for irrigation of the rice farms if bioenergy was not used, labour and transport costs for collection and transportation of the rice straws and husks to a conversion plant.

Financial gain from the use of bioenergy is an estimate from prevailing costs of diesel and selling price of rice at the local market in Malawi using equation (8.3).

$$\mathrm{FS} = P_d * Q_d + S_p * Q_R \tag{8.3}$$

Where:

FS is the financial saving from fossil diesel (US$)

P_d is the pump price of fossil diesel (US$/litre)

$\mathrm{Q_d}$ is the quantity of fossil diesel offset by using the bioenergy (kg/litre)

$\mathrm{S_p}$ is the Selling price of rice (US$/kg)

$\mathrm{Q_R}$ is the quantity of rice produced from irrigating powered by bioenergy (kg)

Table 8.2: Factors used in evaluation of cost of generating electricity from rice straws and husks in Karonga district in Malawi using small scale gasifiers

Parameters[1]	**Description**	**Parameter**	**value**
Gasifier type	Downdraft	Feedstock (500 kg/hour of rice straws and husks at 10 – 15% mc[2] air dried) (tonnes)	1656
Engine capacity (kW_E) Rated	250.	Feed cost (10 - 15% mc[2] air dried) per annum (US$)	57364.71
Engine capacity (kW_E) net	200	Feedstock pre-treatment cost per annum (US$)	125326.80
Engine make	Cummins GTA	Utilities cost per annum (US$)	2592.00
Engine model	1710 G	Maintenance costs per annum (US$)	18074.11
Electrical efficiency (%)	24.5	Labour cost per annum (US$)	43200.00
Feedstock requirement (kg per hour)	400 – 500	Total capital cost (US$)	361482.15
Moisture content (%)	10 – 15	Annual cost of capital (US$)	24098.81
Feedstock particle size (mm)	15 – 70	Overheads cost per annum (US$)	36148.22
Capital cost (plant cost, civil works, installation and commissioning straws bale presser) (US$)	361 482	Total annual operating cost (US$)	194004.65
		Generation cost of electricity per kWhe[2] (US$)	0.13

[1]Sourced from suppliers of gasifier; web page: - www.radheengineering.com
[2]Moisture content; [2]kilowatt-hour of the electricity

8.2.4 Water requirement for rice production

The net water requirement per hectare for rice production by irrigation has been evaluated from the daily water requirement for rice production for dry planting, including water for evapotranspiration of between 38 and 77 m^3 per day as indicated in literature (Chapagain &

Hoekstra, 2011; Adeniran, et al., 2010). The size and power rating of the water pump was estimated using equation (8.4) from (Douglas et al., 2005).

$$\text{Power rating of the pump } = P_{h\,(kW)}/\eta = \left(\frac{Q\rho g H}{3.6x10^6}\right)/\eta \qquad (8.4)$$

Where

$P_{h\,(kw)}$ is the hydraulic power in kW.

Q is the flowrate of the water required for irrigation in m^3/h

ρ is the density of water in kg/m^3

g is gravitational acceleration in m/s^2

H is total dynamic head (TDH) in m

η is the efficiency of the pump

The number of hectares that can be irrigated using the bioenergy from the rice straws and husks was estimated using equation (8.5).

$$N = \left(\frac{P_{ER}}{H * P_{r\,(kW)?}}\right) \qquad (8.5)$$

Where:

N ia the number of hectares that can be irrigated

P_{ER} is the overall energy generated from the rice straws and husks in TWh

H is operating hours of the pump (h)

$P_{r\,(kW)}$ is the power rating for the pump for irrigating unit area of land in kW.

8.2.5 Carbon emissions savings

The environmental impacts have been evaluated by assessing the net savings on carbon emissions as a result of utilising electricity generated from the rice straws and husks to run irrigation water pumps instead of fossil diesel (Equation 8.6).

$$\text{Carbon emissions saving} = \frac{N\left(R_p * C_f * H * D\right)}{1000} \qquad (8.6)$$

Where:

N is number of hectares of the rice farms that can be irrigated

R_p is water pump rated power (kW)

C_f is carbon dioxide emission factor of fuel (g/kWh) (APIC, 2009; IEA. 2009)

H is water pumping hours per day (h/day)

D is days of pumping water into the rice field (day)

The carbon emissions factors were derived from [18, 52-53] and are presented in Table 8.4.

Table 8.3: Parameters for evaluation of carbon emission and costs benefits of an integrated bioenergy and rice production system

Parameter	Value
Carbon emission factor of diesel generated electricity[1] (g/kWh)	670
Water required for rice production per hectare[2] (m^3 per day)	59.4
Water pumping rate (m^3 per hour)	3.3
Water pump rated power (kW)	3
Daily water pumping (h)	18
Number of days of water pumping per planting season of rice.	120
Water pump fossil diesel consumption rate (L/ kWh)	0.392
Quantity of fossil diesel required for irrigation per ha (L)	2540
Pump price of fossil diesel in the base year US$/L	1.08
Carbon emission per hectare (tonnes)	4.3
Acreage that can be irrigated using bioenergy in the base year (ha)	2367
Mean rice yield per hectare of dry planting (tonnes)	4.43
Rice selling price in the base year pr kg (US$)	0.65
Total CO_2 emissions offset by bioenergy in the base (tonnes x10^3)	10.18
Financial saving from diesel purchase in base year US$ (x10^6)	6.58
Revenue from excess rice sales in base year US$ (x10^6)	6.82
Cost of chemical fertilizer per ha (US$)	137
Labour cost per ha (US$)	780

[1] source [52]; [2] Source [48]

8.3 Results and discussion

A mean production of 44117 and 6307 tonnes per annum of the rice straws and husks respectively were estimated from rain fed cultivation of rice farms in Karonga district over the period of 10 years. Collectable portions were estimated at 40% and 65% of the rice straws and husks, respectively. The contextual factors that would influence the use of these bioresources for bioenergy production are discussed in the subsequent sections.

8.3.1 Contextual factors influencing integration of rice and bioenergy production in Karonga

Karonga district (Fig. 1.2b) is located in northern part of Malawi between latitude 9^{o} $57^{'}$ S and longitude 33^{o} $58^{'}$ E covering 3355 km² with a wet and dry savanna climate. Daily temperature ranges between 30 and 40 degree Celsius in dry and hot summer. Total annual rainfall in the district is estimated at about 800 mm (800 litres/m^2), received between the months of December and April is conducive for cultivation of rice and other crops in the district. The district has a high population density estimated at 80 people per km^2 (Malawi Population and Housing Census Report, 2008) with a population growth rate of about 2.8% per annum. The high population growth rate is increasing pressure on arable land to meet the food demand. Rice is one of the major crops grown for food and as a cash crop. Rice is predominantly cultivated in low-lying arable land and valleys that are flooded with water from rainfall runoff.

Karonga district is bordered by Nyika highlands to the west and Lake Malawi to the east (London School of Hygiene and Tropical Medicine). The highlands are the source and catchment area of perennial rivers and stream which flow through the district into Lake Malawi (Fig 1.2b). The deceleration of the water velocities, as the rivers and streams flow through the lowland and the lakeshore into Lake Malawi, provide the opportunity for rice farming during the rainy season. Thus, three rice schemes: Hara, Wovwe and Ngerenge were established by the Government of Malawi (GoM) in early 1980s for rice production in the district. Besides the three rice schemes, rural communities living in the low-lying areas grow rice and other crops for own consumption and for sale. Excess rice that is not needed for own consumption by the rice farming households is sold to the urban population in the district and neighbouring towns at US$0.65 per kilogram.

Irrigation of the rice farms (dry planting) has the potential to increase rice yield per unit area of land per annum through intensive planting per year, which would enhance food security in the district. The Lake Malawi that borders the district to the east provides a secure source of water that can be used for irrigation during dry season. However, such an opportunity has not been exploited. The lack of energy that can be used to power irrigation pumps is a major limiting factor to promoting dry cultivation of rice in the district. Consequently, rice farming in the area has been restricted to rain fed cultivation. Thus, availability and supply of reliable and secure energy is critical to promote productivity as well as unit operations such as processing and preservation of rice that would reduce postharvest losses and enhance profitability of the overall rice crop value chain.

In the survey conducted in rice farms and rice mills in the district, it has been observed that the rice straws and husks are poorly managed. The residues are burnt in the field and at the rice processing mills without utilising the released energy. In some cases rice farmers and the communities around the farms graze their livestock in the rice fields after harvesting and before the next planting season. Some rice husks are collected from the rice processing mills for curing bricks and for use in commercial poultry production. The aforementioned uses of rice straws and husks, if not regulated may constitute competing uses that would affect availability for bioenergy production.

Regulations on utilisation of the rice straws and husks have not been established in Malawi. The lack of regulations has the potential to cause variation in the supply chain of rice straws and husks as a result of unpredictable demands on the resources, which in turn may affect feedstock supply for bioenergy production. The potential pathways of the rice straws and husks and corresponding quantities identified and estimated, respectively, through interviews with agricultural experts and the rice farmers at Hara rice scheme are presented in Figure 8.1

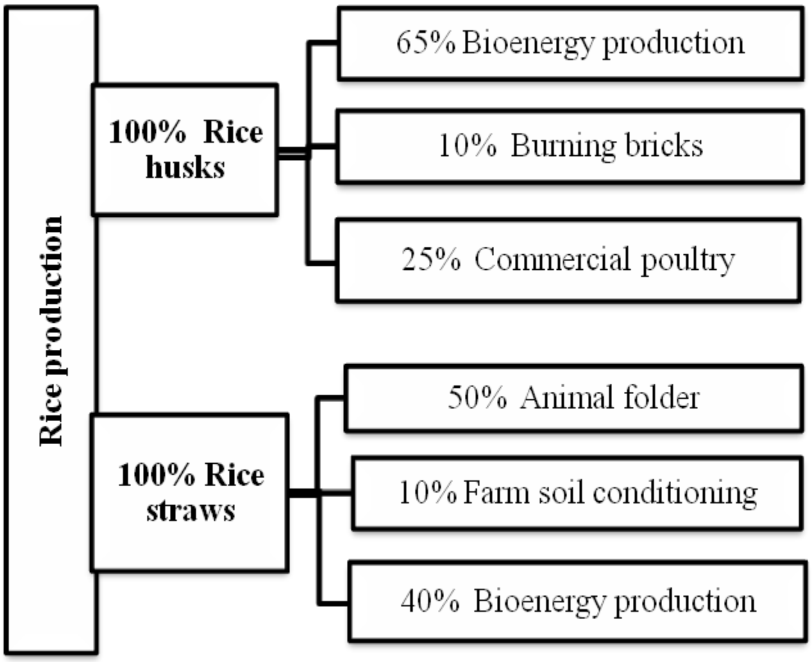

Figure 8.1: Potential pathways of utilisation of rice straws and husks in Karonga district.

8.3.2 Rice residues production and availability of rice straws and husks as feedstock for bioenergy production

The availability of bioenergy for irrigation pumping would allow multiple planting of rice, thus, increasing land productivity (rice yield per unit of land per annum) in the farms. Over the period a 10 years (2005– 2014), rice production in Karonga district increased from 12533 to 37925 tonnes, representing an increase of 200%. Consequently, the quantities of rice straws and husks in the district correspondingly increased overtime as shown in Fig. 8.2. The rice straws and husks increased from 22020 and 3346 tonnes in 2005 to 66634 and 10126 tonnes, respectively, in the 10-year period.

The increase in rice production over the 10-year period was attributed to the expansion of arable land used for rice production and increase in application of chemical fertilizers. Table 7.4 shows the arable land used for rice production and rice yield in Karonga district between 2005 and 2014. Land used for rice production increased by 63% between 2005 and 2014, while the government provided chemical fertilisers to farmers in the farm input subsidy programme (FISP) introduced in 2004 (Wendy, 2013). The increase in rice production as a result of expansion of arable land and application of chemical fertilizers may not be feasible in the future. Critical factors that will inhibit this increase include: diminishing suitable arable land resource along the valleys and streams for cultivation of rice that requires flooded water supply, competition for land for infrastructure development to meet the needs of the rapidly growing population at 2.8% per annum in the district, and unsustainability of the short and medium term approach of the chemical fertilizers subsidy programme that was aimed at enhancing food security in Malawi. Multiple cropping of rice promoted by irrigation pumping that is powered by bioenergy from the rice straws and husks produced in the rice farms, can contribute to sustainable increase of both rice (food crop) yield per unit of land and bioenergy production without requiring extra land resource.

Figure 8. 2: Trend in a10-year historical rice straws and husks production in Karonga District

About 9.4% of the arable land used for rice production was irrigated in 2014 (Table 8.5) mainly by gravity fed at Hara and Ngerenge rice schemes. The gravity fed irrigation system is inadequate and limited to specific terrain of the streams and valleys unlike electric powered irrigation systems which can be developed and installed at any location of the rice farms. Owing to lack of energy in the district, about 90% of the rice farms depend solely on wet planting. The results also show that a higher mean rice yield of 4.43 tonnes per hectare was obtained from irrigated land (dry planting) than a yield of 2.53 tonnes per hectare obtained from the rain fed (wet planting). Therefore, if bioenergy from the rice straws and husks can be targeted to irrigation of the rice farms, it can significantly contribute to increasing rice production by 1.9 tonnes per hectare (75% of the wet planting). The approach has the potential of increasing availability of the rice straws and husks for the bioenergy production system and simultaneously, enhance food security.

Table 8.4: Arable land used for rice production and rice yield in Karonga district

Year	Total Yield (tons)	Land used (ha)	Land not irrigated (ha)	Yield/ha (tons/ha)	Irrigated land (ha)	Yield from irrigated land (tons)	Yield/ha (tons/ha)
2005	12533	8189	8189	1.53			
2006	10284	4714	2644	2.27	1035	4292	4.15
2007	14612	7439	5401	1.90	1019	4344	4.26
2008	25020	10110	8076	2.54	1017	4508	4.43
2009	27093	9718	7558	2.93	1080	4934	4.57
2010	28559	10440	8238	2.86	1101	5045	4.58
2011	30390	11133	8665	2.90	1234	5274	4.27
2012	29973	11661	9233	2.67	1214	5322	4.38
2013	37925	13167	10665	3.00	1251	5880	4.70
2014	34703	13362	10840	2.68	1261	5666	4.49
Mean	25109	9993	7951	2.53	1135	4534	4.43

8.3.3 Electricity generation from rice straws and husks

The rice straws and husks that would actually be collected from the rice farms and processing mills for electricity generation, after accounting for the amounts used for competing uses (Fig. 7.1) could generate about 16.64 GWh in the base year, from the small scale gasification systems that can supply electricity with 95% confidence of supplying the hourly water pumping requirement. The electricity generated could meet about 17% of the energy demand of rural households in the district with average daily energy demand of about 6 kWh per household as per calculations made based on information from literature (Zalengera et al., 2014).

8.3.4 Bioenergy allocation to irrigation of rice farms

The daily water demand of 59.4m^3 (≈ 712.8mm per annum) per hectare is required for the dry planting to promote intensive rice farming in Karonga rice farms. An integrated bioenergy and rice production system can be realised by allocating the bioenergy to irrigation of the rice farms first to increase rice production. About 3.3 m^3 of water per hour pumped for 18 hours per day is required to meet the water requirement for rice production per hectare. A water pump rated about 3 kW would require 6480 kWh per hectare to supply the daily water demand in 120 days of rice cropping. In addition, the small scale biomass gasifiers would require about 1656 tonnes (500 kg/hr plus a factor of safety of 15%) of feedstock to generate the electricity during the dry planting season. The net amounts of rice straws and husks (26414 tonnes) that would be available in the base year after accounting for competing uses (Fig. 8.3), would allow installation of about 16 small-scale gasification systems described in Table 8.2. The energy generated from the gasifiers would power irrigation pumping for 2367 hectares of the rice farms in the base year, resulting in an increase of rice production of about 30% (10486 tons) (Fig. 8.3a). The increase in rice production would subsequently increase availability of rice straws and husks for bioenergy production.

Simulation of rice and bioenergy production over a projected 15 year period (Fig. 8.3a) shows the increase in both rice and bioenergy production as a result of supplying the bioenergy from the rice straws and husks to irrigate the rice farms, in turn increasing the size of the land that could be irrigated. The land irrigated using bioenergy would increase from 2367 to 13537 hectares in the 10th cycle of dry planting (Fig. 8.3a), thus dry planting will cover the same size of land as in wet planting. Rice production would correspondingly increase from 34703 to 59970 tons per annum by the 10th year, representing a73% increase in yield of rain-fed production only, which subsequently, would increase bioenergy generation from the rice straws and husks from 15.34 to 87.72 GWh per annum. If agricultural practices and climate conditions for rice production remained constant, a synergetic integration of bioenergy and rice production can significantly contribute to double cropping, increasing both rice (food crop) and bioenergy production in the rice farms in Karonga district.

A comparison of the extensive rice farming (extensive agriculture) or change of land use that depends on rain-fed production, based on the rice yield per hectare from rain-fed cultivation presented in Table 8.5 and the intensive rice farming using bioenergy for irrigation of the rice farms in Figure 8.3 indicates that 23704 hectares would be required or would be taken away from production of other crops to produce the rice to the same amount as obtained in the 10th cycle of allocating the bioenergy to irrigation of the rice farms.

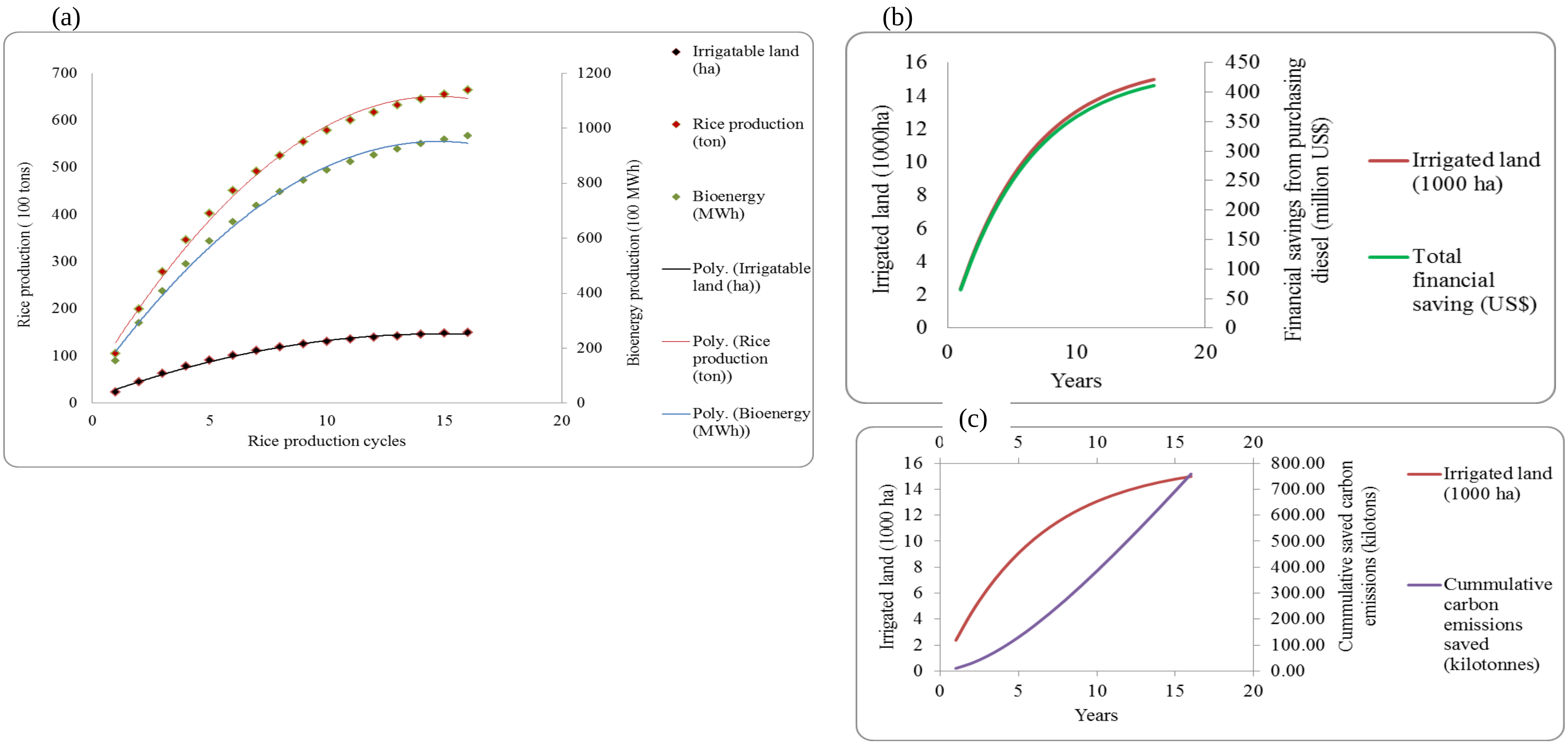

Figure 8.3: Increase (a) in rice and bioenergy production and irrigatable land in a synergitic integrated bioenergy system over a projected period of 15 years. Equations $y = -276.01x^2 + 8142.5x + 4993.9$, $y = -403.73x^2 + 11910x + 7304.8$ and $y = -62.305x^2 + 1838x + 1127.3$ are trendlines for rice production, bioenergy production and irrigatable land. All equations have R^2 of over 0.995, (b) Financial savings from purchase of diesel for irrigation of the rice farms and (c) Carbon emissions saved from using diesel for irrigation of rice farms.

Thus, allocation of bioenergy, produced from the rice straws and husks, to irrigation of the rice farms can reduce competition for land utilised for production of other crops while increasing availability of rice and the feedstocks for bioenergy production. Table 8.6 provides current and potential scenarios of rice production: (i) base case, the existing scenario in the district of rain fed rice production with only 9.3% of the land irrigated using gravity fed irrigation system, (ii) rain fed and 100% of the land irrigated using fossil fuels, and (iii) rain fed with about 100% of the land irrigated using bioenergy.

Table 8.5: Comparison of rice production from three sources of water supply

Scenario	*Basd case – Rain fed*	*Fossil fuel irrigated*	*Bioenergy irrigated*
	Rain fed + 9.3% of land irrigated by gravity.	Rain fed + 100% Fossil fuels powered irrigation.	Rain fed + 100% Bioenegy powered irrigation.
Land - Rain fed (ha)	13362	13362	13362
Mean Yield/ha - Rain fed (ton/ha)	2.53	2.53	2.53
Irrigated land (ha)	1261	13362	13362
Mean Yield/ha – irrigated land (ton/ha)	4.43	4.43	4.43
Mean rice yield/annum (ton)	39392.09	92999	92999

8.3.5 Cost benefit analysis and profitability evaluation of using self-generated bioenergy in rice farms

Electricity generated from the rice straws and husks in the 250 kW_E downdraft gasifiers would cost about US0.13 per kWh. Key elements used in calculation of the cost of electricity are presented in Table 8.3. Although the collection of residues from the farms and processing plants would be considered free of charge, the labour costs incurred in baling of the straws and comminution and transportation contribute significantly to the cost of feedstock and the cost of generating the electricity. Discounted cash flow evaluation of investment in electricity generation from the rice straws and husks using the small-scale gasification systems shown in Figure 8.4 shows that, at lending rate of 35%, offered by financing institutions in Malawi at the time of the study, would breakeven in the 8th year at electricity selling price of US$0.166 per kilowatt-hour of the electricity. However, the price is higher than the average subsidised price of electricity from hydro in Malawi (US$0.094 per kilowatt-hour). A fiscal policy that can support reducing the cost of investment in the bioenergy technologies can increase the competiveness of electricity from the bioenergy systems with the subsidised grid electricity from hydro systems in Malawi.

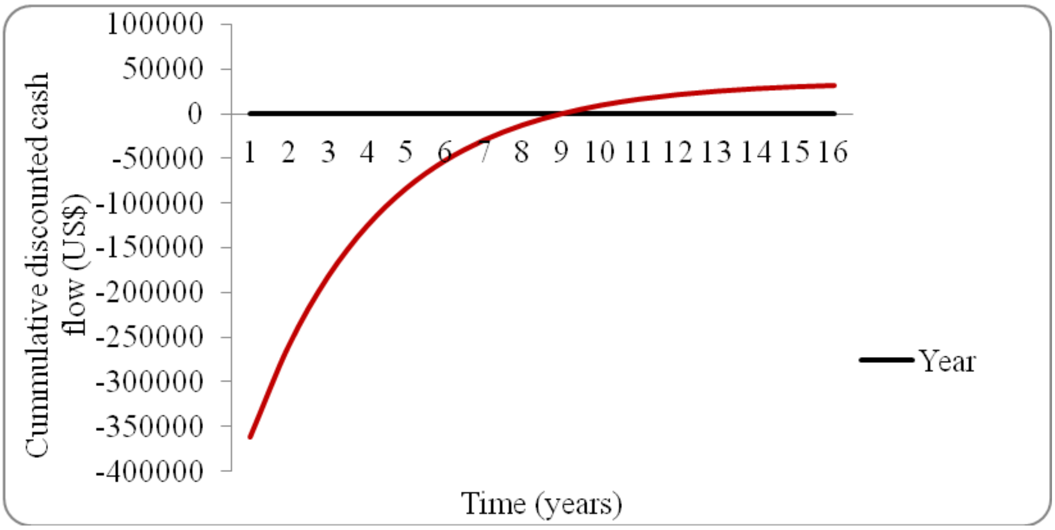

Figure 8.4: Cumulative discounted cash flow for the electricity from rice straws and husks at selling price of US$0.166 per kilowatt-hour

Rice production would increase by investing in water pumps powered by diesel or grid electricity. In the base year, 6040 kilolitres of diesel would be required to run the pumps for irrigation of the same amount of land as irrigated by pumps powered by electricity from rice straws and husks.

About 10.28 kilotonnes of CO_2 would be emitted from the diesel pumps, which would contribute to carbon footprint of 0.98 kg CO_2/kg of rice. It can be observed in Table 8.7 that the total annual operational costs of diesel water pumps amount to US$6505803 to irrigate the same amount of land as irrigated by pumps powered by electricity from rice straws and husks in the base year compared to US$194005 for the gasification system and US$224838 for diesel generator. Thus, using the straws and husks for onsite generation of electricity for irrigation pumping of the rice farms has multiple environmental and economic benefits to the rice farmers in the district.

Although rice production would also be increased by investing in water pumps powered by fossil fuels or grid electricity (Table 8.6), major limitations include the volatility in supply and prices of fossil fuels combined with inadequate electricity generation capacity in Malawi. The cost of the generating electricity from diesel is higher than gasification system as a result of the inherently high operational costs attributed mainly to the cost of acquiring and distributing the diesel. Volatility in supply and prices of fossil fuels are eminent challenges in Malawi, which result in fuel supply uncertainty, consequently, increasing financial burden on the farmers. In contrast, farmers will have some level of control of the cost of acquiring and processing the rice residues into bioenergy in the value chain because of the duo role they have, as feedstock suppliers and as the end users of the bioenergy.

Table 8.6: Total annual operational costs and of gasification of rice straws and husks system and fossil diesel powered systems of similar power output for irrigation of the rice farms.

	Rice straws and husks gasifier	**Diesel water pumps**	**Diesel generator**
Energy yield (kWh)	16.64×10^6	16.64×10^6	16.64×10^6
Capital costs (US$)	361482.15	-	-
Feedstock (fuel) cost (US$)	57365	64936563	158957
Irrigated area in base year (ha)	2367	2367	2367
Total annual operating costs (US$)	194005	6505803	224838
Cost of energy (COE) (US$/kWh)	0.13	0.42	0.15

Bioenergy from rice straws and husks used for irrigation of the rice farms would enable rice farmers save up to US$6.58 million in the base year of irrigating 2367 hectares, from buying fossil diesel besides maintenance costs of the diesel water pumps. In the 15th year of the bioenergy systems, farmers would save more than US$223.28 million when the cost of fossil diesel is accounted for (Fig. 8.3b).

The increase in rice production would also increase gross income to the farmers of about US$6.82 million from sales of the rice from dry planting using the bioenergy in the base year. The gross income would cumulatively increase to US$253.31 million by the fifteenth year (Fig 8.3b). Key expenditures incurred by the rice farmers on inputs and labour were estimated at about US$137 and US$780 per hectare respectively. Thus, the farmers would gain a net income of about US$4.65million from sales of the rice from dry planting of 2367 hectares in the base year and US$172.64 million in the fifteenth year (Fig 8.3b). The total financial gain from savings from purchase of diesel and from sales of the rice from dry planting would be US$179.81 million in the fifteenth year of targeted supply of bioenergy to irrigation of the rice farms (Fig 8.3b).. Thus, the synergetic integration of bioenergy and rice production approach has the potential to increase both food and bioenergy production with multiple environmental and socioeconomic benefits to the farmers.

8.3.6 Integrated bioenergy and rice production system

Rice farming in Karonga district is constrained to low-lying arable land along the valleys that receive adequate water supply from both rainfall and runoff from upland areas. Intensive and extensive rice farming, including change of land use for rice production, require intensive input of energy for water pumping for irrigation of the farms to meet the daily water requirement of the rice crop. The results presented in Section 8.3 and Section 8.4, indicate that in the base year about 18.3 GWh_E would be generated from the straws and husks that can realistically be collected from the rice farms and processing mills, after accounting for the straws and husks that are collected for other uses. The bioenergy from rice straws and husks from wet planting of the rice would provide the initial input energy in the base year for irrigation of 2367 hectares of the rice farms for dry planting, thus allowing double cropping per hectare per annum which would increase the rice yield per hectare per annum. The results in Figure 8.3a show that increasing rice yield per hectare per annum in the rice farms through irrigation would increase the amount of the rice straws and husk that would be available for bioenergy production that is synergistically integrated with rice production.

Promotion of off-season rice irrigation enhances intensive land use and increase rice yield per unit of land per annum. The approach can be augmented by other practices such as the use of high yield rice varieties and reduction of post-harvest losses to raise the yield ceiling per cropping season per unit area of land (Labortea et al., 2012; Lu, 1991; Koning & van Ittersum, 2009) thus, increasing the rice production and food availability without seeking for extra land resource. Furthermore, the approach can advance integration of agriculture and bioenergy production systems in other agricultural systems as presented in Table 8.8 (Maltsoglou et al, 2015). In the absence of intensive input of energy for pumping water for irrigation of the rice farms, the water requirement for the production of rice is a critical limitation to multiple cropping (intensive rice farming), the expansion of arable land (extensive rice farming) and land that can be freed from other crops (change of land use) for rice production.

Table 8.7: Suggested approaches to integrating bioenergy in agriculture in Malawi

	Approach	Objective
1	Intensive agriculture	Produce more food crop per unit area of land than food requirement and use the surplus yield for bioenergy production.
2	Extensive agriculture	Open more arable land (expansion of cultivated arable land) to produce more food crop than food requirement and use the excess yield for bioenergy production.
3	Change in land use	Make bioenergy crops more economical with better prices than current cash crops in the area/region to motivate farmers to cultivate energy crops
4	use of crop residues	Utilise wastes for bioenergy production

A schematic flow of an integrated rice and bioenergy production system that would prevail at the rice farms in a looped process design is shown Figure 8.5. The rice from dry planting using the gravity fed irrigation is harvested in November just before the start of the rainy season. In a normal rainy season with estimated precipitation of about 800mm, irrigation is least required in the district. In addition, animal folder is provided from green pasture and moulding and curing of bricks is suspended during the rainy season. Only 10% of the straws and 25% of the husks from dry planting used for soil conditioning and commercial poultry respectively (Fig 8.1) would not be available for bioenergy production. As a result, the straws and husks produced from dry planting could be combined with those produced from the wet planting, increasing and promoting sustainable supply of feedstock for bioenergy to be used in the next dry planting.

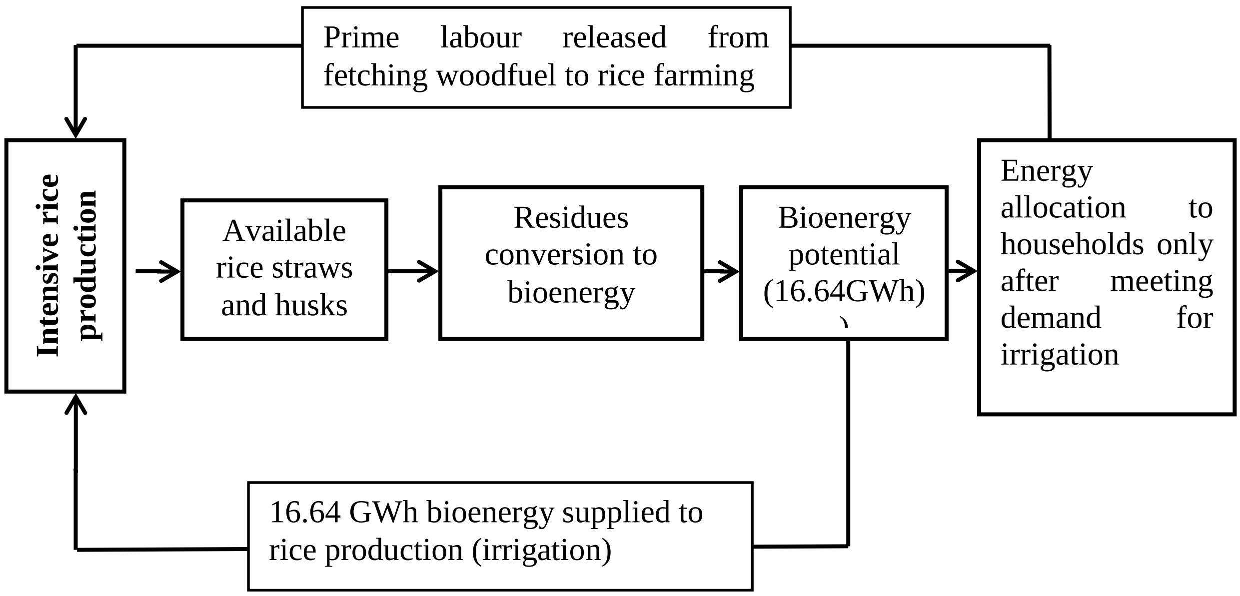

Figure 8.5: Integrated rice and bioenergy production systems flow diagram

Alternatively, bioenergy could be produced during the rainy season to supply to about 200 households for home use and other productive farming activities such as post-harvest processing of the rice and residues generated during wet planting. Excess energy, not required for irrigation could also be used to reduce labour bottlenecks for rice management, which would reduce the varience between actual and expected feedstock yield. Agricultural residues from the other crops grown in the district , can provide supplementary feedstock to the rice straws and husks to enhance the boenergy system availability and reliability of energy supply.

Women constitute about 60% of the prime labour in the rice farms. However, women are also responsible for collection of fuelwood for household energy needs. Thus, bioenergy can have multiple benefits of reducing the burden of fetching for firewood on women thereby allowing the prime labour to concentrate on rice production with the potential of improving management of the rice farms and increasing rice production.

8.3.7 Environmental benefits of the rice straws and husks bioenergy value chain

Bioenergy production from the rice straws and husks in the rice farms in Karonga district would reduce the potential fire risk from the husks that accumulate in piles at the rice processing mills. It would also reduce emission of methane gas from gradual biodegradation of the rice straws that are not utilised in the farms and the husks at the rice processing mills. Thus, promoting sustainable disposal and improving the aesthetic of the environment around the mills. Furthermore, the bioenergy would offset fossil fuels that would have been used for irrigation of the rice farms to obtain similar increase in rice production.

The use of fossil fuels has both local and global environmental effects from greenhouse gas emission. Evaluation of carbon emissions from fossil diesel that would have been used for irrigation of the 2367 hectares of the rice farms indicates that about 8.82 kilotonnes of CO_2 would have been emitted in the base year (Fig, 8.3c). An integrated bioenergy and rice production supplying the bioenergy to irrigation of the rice farms would cumulatively offset about 285.33 kilotonnes of CO_2 in the projected period of fifteen years of the lifespan of the bioenergy conversion plant (Fig 8.3c).

8.4 Conclusion

The rice straws and husks that are produced annually in the rice farms and rice processing mills in Karonga district in Malawi can be utilised to enhance both bioenergy production and rice production systems without taking away land from cultivation of other crops. The approach has shown potential to enhance incremental investment and deployment of modular decentralised small-scale bioenergy and irrigation systems in the rice farms when more straws and husks are produced from dry planting. Therefore, enhancing food crop productivity per unit of land and food security when adopted and implemented in the rural agricultural sector in Malawi. Strategically targeted bioenergy production in rice production would enable diffusion of bioenergy technologies in Karonga district with potential for adoption in other districts in Malawi and beyond where rice is also grown.

Bioenergy from the residues supplied to irrigation of the rice farms has environmental benefit of offsetting carbon emissions from fossil diesel which would have been used to irrigate the farms if bioenergy was not used, and reducing the fire risks at the rice processing mills. The direct economic benefits of the approach to the rice farmers include financial savings from purchasing the fossil diesel for irrigating, and additional revenue from sales of excess rice produced from dry planting as a result of using the bioenergy. Thus, the synergetic integration of bioenergy and rice production, using the rice straws and husks, provides a bioenergy/food nexus with the potential to enhance food security and sustainable energy supply simultaneously, with environmental and economic benefits in the rural rice farming communities in Karonga district in Malawi. Realisation of this potential will depend on improving the handling, management and processing of the bioresourcre and formulation of regulations to synchronise the use of rice strwas and husks for bioenergy production and competing uses such as straws for soil conditioning and folder for livestock, and husks for commecial poultry and curing of bricks for construction.

Chapter 9: General discussion and conclusion

A systems approach, based on systems thinking and system dynamics modelling methodology, in combination with the conventional methods of residues to product ratio, onsite forest residues inventory, bioenergy potential and macro-economic viability evaluation, and a layered five-step sustainability analysis, was used to assess sustainability of residues-based bioenergy production. The approach was used to assess sustainability of two residues-based bioresources: perennially produced primary forest residues from Viphya forest plantations and annually generated rice residues in rice farms in Malawi. A systems approach model for sustainable production of bioenergy (SAS-Biopro model) was developed for the residues value chains. The SAS-Biopro model demonstrated that integration of bioenergy and timber production systems in forest plantations, and bioenergy and rice production systems in rice farms, can promote resilience of the primary forest and rice residues supply chains and sustainable production of timber, rice and bioenergy over time. The resilience of the residues-based bioresources supply chains for bioenergy production, against contextual changes in technologies, process operations and policies over time, in the primary systems that generate the residues, is a critical component of sustainability of the residues-based bioenergy systems.

9.1 Resilience of the residues supply chain as sustainability criteria for residues-based bioenergy systems

Resilience of the residues supply chain was defined in section 2.7 in chapter 2 as steady production, availability and reliability of supply of sufficient amount of the residues for bioenergy production to meet the feedstock requirement of an optimum bioenergy conversion plant scale over time. Systems approach modelling of the primary forest residues value chain has shown that steady flow of primary forest residues to a bioenergy conversion plant can be promoted through synchronization of harvesting and replanting of the forest plantations, and establishment of thresholds for harvesting the forest plantations per annum to generate residues at a rate that can match with the scale and rate of operation of the bioenergy conversion plant.

In addition, systems approach modelling of the forest residues value chain has demonstrated that the total area of the forest plantations and maturity age of the tree species replanted on the harvested sites are key parameters for evaluation of the threshold for annual harvesting the mature forest stand. Matching the scale and rate of operation of a bioenergy conversion plant with the residues generated from annually harvested threshold of the mature forest stand promoted stability, availability and reliability of timber and primary forest residues supply for bioenergy production over time. Thus, establishing harvesting threshold of mature forest stand and synchronising harvesting and replanting of the harvested sites can promote positive net-flow of mature forest stand for timber production, which in turn can provide steady net-flow of primary forest residues to the bioenergy conversion plant over time.

In the Viphya forest plantations, the SAS-Biopro model showed that an annual allowable cut of 1240 ha pear year (7 ha per sawyer per year for the 175 sawyers operating in the plantations), synchronising harvesting and replanting and reducing the mortality (death) fraction of the replanted trees to ≤0.1 would promote steady availability of about 3700 ha of mature stand, 1240 ha of maturing stand and about 28500 ha of immature stand over a time horizon of 100 years. In addition, the model has showed that managing and harvesting the Viphya forest plantations under these conditions can promote constant cover of growing forest (maturing and immature trees) that promoted carbon sequestration and supported ecosystem balance over time. Therefore, management and harvesting systems of the forest plantations and matching the scale and rate of operation of a bioenergy conversion plant with the residues generated from annually harvested mature forest stand threshold can promote positive and sustainable bioenergy/timber production nexus in forest plantations established and managed exclusively for the purpose of timber production in Malawi.

The SAS-Biopro model for the rice residues value chain showed that targeted supply of the bioenergy from rice residues to irrigation water pumping, to promote double-cropping of rice, simultaneously increased rice, rice residues and bioenergy production in the rice farms. Variations in the supply chain of the residues were mainly from the demand of the residues for competing uses, especially animal fodder during the hot and dry summer in the case study area. Rice straws from rain-fed rice production decreased with increasing animal population over time (Fig. 5.8a in Chapter 5). As a result of the limitation of suitable arable land for expansion of the rice farms, rain-fed rice production is constrained to 13362 ha (Table 8.4), which also limit the amount of rice and rice residues that can be produced from rain-fed rice production. Thus, deployment strategy of synergetic integration of bioenergy and rice production developed in this study, presented in Figure 5.9 in Chapter 5 and discussed in 8.3.6 in Chapter 8, is an innovative approach that can contribute to increasing rice, rice residues and bioenergy production without alienating land from production of other food or cash crops.

As observed in simulation and analytical results in Fig. 5.10 in Chapter 5 and Fig. 8.3 in Chapter 8, respectively, multiple cropping can promote steady production of rice residues and hence, resilience of residues supply for bioenergy production over time. Owing to availability of alternative animal fodder and minimal requirement for irrigation in the rainy season, rice straws from wet planting would be collected for bioenergy production supplied to the households in the rice farming communities (Fig. 8.5 in Chapter 8).

9.2 Research findings

This study assessed sustainability of residues-based bioenergy systems. This work has demonstrated that management and process operations in the primary systems that generate residues-based bioresources that can be used for bioenergy production, have significant influence on variations in stocks of the residues that can be produced and supplied to a bioenergy conversion plant over time. Residues-based bioresources supply chains for bioenergy production are complex and comprise interconnected and interacting components, which can be enablers or disenablers to sustainability of the residues-based bioenergy systems. Using the systems approach modelling techniques, the SAS-Biopro model has been developed in this study.

Simulation results of the model, for the case studies of primary forest and rice residues from Viphya forest plantations in Malawi, have revealed that sustainable production of primary forest residues-based bioenergy requires holistic integration of forest management and bioenergy production. Specifically, establishing annual harvesting threshold of mature stand evaluated from the total area of the forest plantations and maturity age of the tree species, and synchronised harvesting and replanting of the harvested sites as a whole system, is critical to promote resilience of primary forest residues supply chain. In addition, this study has shown that the modelling approaches used to estimate techno economic parameters of bioenergy production as linear systems in equilibrium (econometrics approach), optimize functions under constrained conditions (linear programming), spatial explicit and event-driven problems (discrete event simulation) have not adequately addressed resilience f the sources of the feedstock as sustainability criterion of residues-based bioenergy production.

Furthermore, this study has shown that deployment of rice residues-based bioenergy if targeted at state limiting process operations in the rice farms can simultaneously promote sustainable bioenergy and rice production. Existing approaches to integration of bioenergy and forest or agricultural farms management have focussed on sharing the costs and benefits of utilising the residues for energy generation between the primary systems and the bioenergy system. However these approaches have not sufficiently addressed process and policy integration so that the two systems can be synchronised to operate as subsystems of a unit system to simultaneously promote steady production of bioenergy and the principle components.

This research has also demonstrated that systems approach modelling technique can be applied to assessment of sustainability of residues-based bioenergy systems to gain insights of the complex and nonlinearities, potential long term imbalance conditions in production and supply of the residues, bottlenecks which may cause delays to steady flow of the residues, stocks and flows relationships and points of high leverage for innovations in the system. The advantage of using dynamic systems approach modelling of sustainable production of bioenergy production from residues-based feedstock supply chains is that it can promote formulation of multidiscipline technical, process and policy innovations that can support holistic integration and sustainable production of residues-based bioenergy and the primary systems.

At technical and investment levels, fragmented approach of forest plantations or rice farm management, including postharvest handling of the residues, and bioenergy production can exacerbate sustainability challenges of primary forest and rice residues-based bioenergy systems. For instance, competing uses of the residues influence variations in availability of the residues, which in turn can cause variations in bioenergy production and supply to end use processes. The variations in bioenergy production and supply to end use processes have negative impacts (repercussions) on economic viability of the bioenergy systems. These variations may decrease profitability of bioenergy development which may result in prolonging the length of time required to recover the cost of an investment (payback period), and on return on investment.

In conclusion, bioenergy from primary forest and rice residues is renewable but its availability and reliability is inherently dependent on the level of integration of forest management and bioenergy systems in forest plantations, and rice farms management and bioenergy production in the rice farms. Whole systems integration of bioenergy and timber production in forest plantations and synergetic integration of bioenergy and rice production in the rice farms can promote sustainable production of both bioenergy and the principal components generating the residues. These approaches can promote sustainability of the ecosystem that depends on the plantations for survival and food value chains without alienating land from food and cash crops production in developing economies.

9.3 Theoretical and practical policy implication of the research

Whole systems integration of bioenergy and timber production in timber plantations and synergetic integration of bioenergy and rice production in rice farms are process innovation approaches developed in this study. As discussed in the preceding chapters and sections, application of these approaches to development and deployment of primary forest and rice residues-based bioenergy systems can promote steady flow (stability) and long term availability (resilience) of residues-based feedstock supply chains for bioenergy production, and availability and reliability of the residues-based bioenergy systems.

Although the SAS-Biopro model has been developed based on primary forest and rice residues value chains, the insights gained from the model can be applied to development, operation and management of bioenergy systems utilising other residues-based feedstock supply chains produced as wastes from primary systems. The findings in this research demonstrate the need for paradigm shift from fragmented, event-oriented open loop thinking to whole system synergetic integration of residues-based bioenergy production and the system that generate the residues.

Sustainability of residues-based bioenergy production will depend on integration of the primary system that generates the residues and the bioenergy system generating energy or energy carriers from the residues as a unit system so that the causal-effects relationships of technical, process and policy innovations developed for implementation in one part of the system are adequately analysed for the whole system, leverage points (enablers and disenablers) are identified and effective policy frameworks and operational guidelines for operation of the whole system are formulated and implemented.

9.3.1 Practical implementation of the findings in the case study areas

Practical implementation of the findings of this study requires involvement of policy makers in energy, forestry and agriculture sectors, sawyers and sawmilling companies in the forest plantations and rice farmers and millers in the rice farms as key stakeholders. Specification of bioenergy producton as the primary use of priary forest and rice residues from Viphya forest plantations and rice farms in Karonga district, respectively, can promote security of supply of the residues to bioenergy conversion plants. Implementation of whole systems integration of bioenergy and timber production in Viphya forest plantations requires policy makers and stakeholders in energy and forestry to:

(i) Establish and implement a mature stand harvesting threshold (annual allowable cut) of 1240 hectares per annum in the section harvested by SMFEs, and synchronise harvesting and replanting as discussed in sections 6.3.5 and 7.3.1 of this dissertation;

(ii) Setting minimum logging and sawmilling technologies efficiencies, and regulate the proportions of these technologies that can be utilised in the Viphya forest plantations;

(iii) Design and sizing the scale of operation of primary forest residues-based bioenergy systems based on the annual residues throughput (yield) from the annual allowable cut of mature stand in the plantations; and

(iv) Mutual mobilisation of resources (financial and personnel) between forest plantations management and the primary forest residues-based bioenergy systems developers, and increasing investment in plantations management to support silvicultural operations and management and control of forest fires.

Similarly, implementation of synergitic integration of bioenergy and rice production in rice farms requires, involvement of policy makers in agriculture an energy sectors and rice farmers to develop a postharvest management plan of the rice residues, taking into account the demand for competing uses. The provision of alternative nutritious animal fodder in place of rice straws during the dry season, when animals graze in the rice farms, was considered a point of high leverage along the rice straws value chain that can increase the proportion of rice straws for bioenetgy production. Rice straws have a low phosphorous content (0.02 to 0.16%) compared to phosphorous requirement (0.3 to 0.4%) needed for healthy growth of animals. In addition, Peripolli et al., (2016); Kumar et al., (2014); Drake, (2002) have observed that rice straws have high content of lignin and silica (8 to 14%) that limit voluntary intake and reduce degradability of the straws by ruminal microorganisms compared to alfafa hay. Training farmers in hay preparation and production in rainy season, when animals graze on natural grass, for feeding livestock in dry season, when animals graze in the rice fields, can increase the proportion of straws for bioenergy production. However, the tradeoffs of rice, animal fodder, livestock and bioenergy production may need further investigation and modelling to understand the behaviour of the system over a long time horizon.

9.3.2 Economic and social implications and tradeoffs of integration of bioenergy in Viphya forest plantations and in rice farms in Karonga district

As observed in section 6.3.3 in Chapter 6 and in section 8.3.5 in Chapter 8, integration of bioenergy in Viphya forest plantations and in rice farms has the potential to create direct and indirect jobs along the forest and rice residues value chains and the bioenergy conversion plant. Direct jobs can be created in residues collection, hauling from the plantations and farms, and feeding and operating the conversion plant. In addition, electricity generated from the residues can create business opportunities associated with access to electricity.

9.3.2.1 Economic implications and tradeoffs on sawyers in the Viphya plantations

Implementation of annual allowable cut of 1240 hectares per annum (7 hectares per sawyer for 175 sawyers) decreases the sawyers' annual revenue obtained from harvesting about 12 hectares per sawyer per annum. In the AAC-IMC scenario, sawyers' income decreases by 33%. However, the 10-year gap observed in the BAU scenario (Fig. 7.6a in Chapter 7), when mature stand are completely depleted as a result of over exploitation of the forest, implies that sawyers' income decreases to zero until after the first cohort of replanted trees have matured (after 25 years) for harvesting. In contrast, the stability in availability of mature stand when harvesting at AAC provides the sawyers with stable income throughout the simulation time horizon (100 years). It can be observed that implementation of whole systems integration in the Viphya plantations can have positive net benefits on sawyers' income over time.

9.3.2.2 Economic implication on rice farmers

Double cropping of rice in the rice farms provides the farmers with the opportunity to generate additional income from sales of excess rice produced from dry planting, besides the income from sales of excess rice produced from wet planting.

It can be observed that implementation of whole systems and synergetic integration of bioenergy production in the Viphya forest plantations and in the rice farms in Karonga district respectively, can have multiple social and economic benefits to the sawyers and the rice farmers.

The findings of this research can promote the uptake of small scale modular decentralised residues-based bioenergy systems in rice farms and forest plantations with technological, economic, and social conditions similar to those of the case study areas in Malawi.

9.4 Recommendation for further studies

The findings from the field survey in the rice farms in Karonga district have shown that rice residues are used for animal fodder, curing (burning) of bricks for construction of houses and in commercial poultry production. The increase in demand for the rice residues to these pathways decreases the amount of rice residues that can be available for bioenergy production. However, both animal husbandry and poultry generate residues which can also be used for bioenergy production. Due to limitations of resources and time, the potential of integrating rice, livestock and poultry, and bioenergy production has not been investigated. Integration of these systems for bioenergy production and the potential dynamics over time, need to be investigated.

The combined effects of the increase in traffic volume in the forest plantations for collection of primary forest residues and the degree of removal of the residues on long term forest site productivity and sustainability of the residues supply chain for bioenergy production may need to be further investigated. The study may require longer time horizon for data collection and observation than the time allocated for the PhD study.

The SAS-Biopro model developed in this study has provided significant insights on the dynamics associated with residues-based bioenergy production. However, the model and the findings need to be presented to the stakeholders where the information was derived from, which may lead to refining it and promote acceptance for implementation. Reengagement with the stakeholders at community and policy levels in Malawi is critical for practical implementation of the findings of this research and is expected to be an ongoing process beyond this PhD study.

The cost-benefit analysis (CBA) of returning land to natural forests instead of forest plantations or crop land (whether it would offer similar benefits, better, or worse), was not considered in this study. This may need to be investigated taking into account The local-scale of plantations and cropland, neighbourhood characteristics, population growth and associated needs may have to be incorporated to investigate conversion and reconversion of land to different land uses. This would also include the causal effect relationships on existing forest management and planning policies; effects of feedbacks structures in the overall land conversion and reconversion processes, factors related to individual preferences, level of economic development, socio-economic and political systems.

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Appendices

Appendix A1: Journal papers published

A1.1: A synergetic integration of bioenergy and rice production in rice farms

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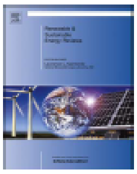

A synergetic integration of bioenergy and rice production in rice farms

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ABSTRACT

Lack of energy for powering irrigation pumps limits off-season production of rice in Malawi. This paper reviews a 10-year historical rice production data from rice farms in Karonga district in Malawi to assess the impact on rice yields and availability of straws and husks for on-site bioenergy production in small scale gasifiers, to power irrigation pumping during off season over a projected period of 15 years. Annual production of rice straw and husks has been estimated using residues to product ratio while taking into account collectable amounts and allocations to competing uses. The heating values obtained from literature and validated by analytical Gross Calorific Values of straws and husks have been used to estimate the bioenergy potential. Irrigation pump capacity and pumping rate calculated from daily water demand, and carbon emissions savings determined from the differences between emissions generated by fossil diesel and bioenergy powered irrigation have been used for calculating environmental benefits. The sales of excess rice provided estimates for financial gains. In the base year, generation of straws and husks of about 44117 and 6703 t and collectable portions of 40% and 65%, respectively, are estimated, providing a total bioenergy potential of 16.64 GWh. With onsite-generated bioenergy, irrigated land can increase from 2367 to 13362 ha while rice and bioenergy production increases from 34703 to 59970 t and 15.34–87.72 GWh, respectively, by the 10th cycle. Cumulative revenue of US $354.60 million from sales of excess rice and net carbon emissions saving of 285.33 kilotonnes can be achieved by using electricity generated for irrigation pumping. Investment costs in electricity generation can breakeven by 8th year if sold at US0.166/kWh. Therefore, on-site generated bioenergy targeting irrigation pumping for off-season rice production is an enabler for promoting positive and sustainable fuel /food nexus in rice farming communities through intensive farming.

1. Introduction

Irrigation pumping is an energy limiting productive unit operation in rice farming in Karonga district in northern Malawi. The lack of energy in the agricultural sector in the district that can be used for irrigation, has confined irrigated rice production to rice schemes with gravity-fed irrigation systems [1–3]. Synergetic integration of bioenergy and rice (food crop) production in rural rice farming communities presents the opportunity to simultaneously meet energy and food demands without requiring extra land resources.

Rice is one of the four main staple food crops grown in Malawi, after maize (corn), cassava and potatoes. Significant quantities of rice straws and husks are produced annually in rice farms and processing mills but they are economically underutilised [4]. The straws and husks can be converted to other forms of energy, besides burning to supply modern forms of energy such as electricity [5–8]. In most rice producing regions, some of the straws and husks are used by the households for cooking and water heating [6,9–13], while large proportions are burnt in open fires in the field as part of land clearing and preparation for next planting season [14] or at the rice processing plants as a means of disposal. Therefore, the energy contained in the straws and husks is wasted when the straws and husks are burnt in the open fires. Bioenergy from the straws and husks could provide potential substitute for fossil fuels that is required to power irrigation pumps and other unit operations in rice production.

Fossil fuels have intensively been used in rice production for powering upstream as well as downstream processes, thus, cultivation, agro processing, packaging and transport to markets [15] but have remained the central component and a limiting factor of agricultural productivity in developing economies. The volatility of the global market of fossil fuels negatively affects the security, availability and reliability of fuel supply in countries like Malawi that largely depend on imported petroleum products. Over dependence on fossil fuels in crop production has resulted in high carbon footprint per unit mass of the crops, variations in costs of crop production overtime and food prices as a result of the frequent variations in fossil fuel prices [16–20].

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On-site production of electricity at the farms that can be supplied to crop production provides potential alternative clean and sustainable source of energy [21], which can be reliable and affordable compared to fossil diesel and electricity from the main grid. In case of rice production, the electricity generated from biomass can contribute to reducing carbon footprint per unit mass of rice and offset the cost of fossil fuels and grid electricity. As a result, holding other factors constant, rice production is likely to increase, thus enhancing food security. The extent to which on-site electricity production can increase rice production, and reduce greenhouse gas emissions overtime and the cost implications on the associated unit operations and the economics of the farming, has not been assessed.

The rice straws and husks that are left at the farming site and rice processing plants, respectively, go through a gradual biodegradation process that releases methane (CH_4) into the atmosphere. Methane is 21 times more potent greenhouse gas than carbon dioxide (CO_2) [22]. Therefore, bioenergy production from the straws and husks has the potential to reduce the methane gas emissions besides contributing to a secure energy supply [23].

Previous studies have reported on potential conversion routes that allow production of diverse forms of energy [4,5] or intermediary energy carriers and co products from rice straws and husks. For example, the physical and chemical characteristics of rice straws and husks [7] provide the opportunity to convert them to heat and electricity in a cogeneration mode or only heat or electricity in a single form of energy generation mode [23–27]. Rice straws and husks can be converted to bio char, bio oils and product gas through pyrolysis and gasification [28–30]. The high content of cellulose and hemicelluloses in the rice straws provides opportunity for conversion of rice straws and husks through biochemical processes of hydrolytic to fermentable sugars for production of bioethanol [5,31–34]. The volatile matter and the fixed carbon in rice husks can be converted to biogas in anaerobic digestion [35–37]. The biogas could be used for cooking in gas stoves or for generation of electricity in spark ignition engines coupled to generators [24].

Viable technology configurations for conversion of rice residues to electricity have been reported in Thailand [7,38], Malaysia [14], India [39] and Brazil [40], which include direct combustion (boiler → steam-turbine → generator) and gasification (gasifier → gas turbine → generator or gasifier → internal combustion engine). Electricity generation using downdraft biomass gasifiers, coupled with internal combustion engines, have shown favourable economies of scale of low capital cost per kilowatt-hour, unlike the biomass → boiler → steam turbine → generator configuration [41,42]. The downdraft gasifiers provide producer gas which has relatively low tar content with acceptable quality for use in internal combustion engines (ICE) for generation of electrify [40]. The restriction on scaling up downdraft gasifiers to a maximum plant capacity of 250 kW [41] provides opportunity for deploying small-scale modular systems in the rice farms in rural areas suffering the lack of electricity.

Rural electrification based on agricultural residues is evidently not a new phenomenon [7,27]. However, the implementation strategy of such bioenergy systems is not effective in promoting sustainable integration with food systems. Consequently, rural communities are expected to access the biomass generated electricity through the main electricity grid where they have very little control and participation. Therefore, the system is characterised by several loopholes that leak benefits directed to the communities. Furthermore, the benefits from the conventional rural electrification programmes to the rural communities are improperly accounted for by considering the number of connected communities rather than what the electricity was used for and the actual impact it made on their livelihoods.

This paper is presenting a closed-loop for integrated bioenergy and rice production system promoted by introduction of on-farm self-generated bioenergy for powering irrigation pumping on rice farms during off season. A case study of rice farms in Karonga district in the northern part of Malawi based on a10-year historical rice production data, is used to demonstrate how bioenergy generation (electricity) from rice straw and husks, if targeted to a specific energy limiting productive unit operation in rice production, can be used as an enabler for promoting positive fuel /food nexus. In this approach, the electricity generated from the rice straws and husks using a small-scale downdraft gasifier coupled with internal combustion engine (ICE) rated 250 kW_E, with capacity factor of 0.8, is specifically applied to power water pumps for irrigation of the rice farms during dry season.

The potential of such targeted bioenergy system to promote positive integration with food production with regards to food security, feed-stock availability, financial returns and greenhouse gas emissions savings has been assessed. In the base year, the bioenergy generated from the rice straws and husks is initially used to power irrigation pumps to irrigate part of the rice farms during dry season. The increase in rice yields increases the availability of rice straws and husk as bioenergy feedstocks for the subsequent cycle. As the bioenergy production capacity increases, the portion of land that is irrigated during off season increases correspondingly.

The approach is considered holistic and strategic for allowing the rural communities to benefit from direct use of biomass generated electricity where it would make the most positive impact in their livelihood. In addition, the partial implementation of the off season irrigation allows communities to gradually adapt to the increase in rice production which might necessitates increasing capacity of down-stream operations. The increase in capacity of the downstream operations can be strengthened by the resilience of the rice straws and husks supply chain overtime. The assessment of the potential for carbon and financial savings and revenue generated from increased rice production, when bioenergy from rice straws and husks is supplied to rice production, is done using fossil diesel and/ or conventional grid electricity as benchmarks.

2. Materials and methods

Data collection involved a field survey undertaken in Malawi with the stakeholders in agriculture (national and division levels), energy and the rural households in rice farms in Karonga district. Data collected using structured and semi structured questionnaires, formal group discussions and from literature captured historical rice production trends in a 10 year period and projected over a 15-year period.

2.1. Assessment of rice straws and husks production

Rice straws and husks produced in rice farms in Karonga district have been obtained from the10-year 2005–2014) historical data on rice production obtained from Ministry of Agriculture in Malawi. The quantities of rice straws and husks generated per annum have been estimated using residues to product ratios reported in literature [43–46]. The annual production of rice straws and husks have been using Eq. (1) reported in [46].

$$R_{CR}=(C \, x \, RPR) \tag{1}$$

where:

R_{CR} is the annual production of crop residues;
C is the annual rice production; and
RPR is the residues to product ratio of rice straws or husks

As a result of unrecorded data on the farms and at the government offices, the proportions of residues collected for competing uses to bioenergy, were estimated through interviews with the stakeholders and experts in the agriculture sector and the rice farmers. Bioenergy potential from the rice straws and husks was estimated using Eq. (2) and the heating value (HV) reported in [33,35,36], which were validated in an experiment using the Standard Test Method for Gross

Table 1
Residues to product ratio and heating values of straws and husks.

	Residues to product ratio	Heating values (MJ/kg)	
		From literature	From experiment
Rice straws	1.757, 1.0:1.4 [46]	8.83 [39], 14.7 at 20% mc [46],	–
Rice husks	0.267, 1.0:1.4 [46]	12.9 [39], 14.7 at 20% mc [46],	13.2 at 8% mc

Calorific Value (ASTM Standard D5865-11A) [47]. Table 1 shows the residues to product ratios and the heating values reported in literature and the heating value of husks obtained in the experiment that was used in this study.

$$Q_{ER}=(RR_T \times LHV) \tag{2}$$

where:

Q_{ER} = the bioenergy potential of the residues in MJ
RR_T = Total rice residues collected from the rice farms and mills in tonnes
LHV = Lower Heating Value of the residues in MJ/kg.

2.2. Electricity generation from rice straws and husks

Electricity generation from the rice straws and husks for supplying power for irrigation pumping in the rice farms and meeting other energy needs of the rural rice farming communities, has been simulated in a small-scale decentralised system using downdraft gasifier with feeding rate of 400–500 kg/h that is coupled with GTA 1710G Cummins engines rated at 250 kW_E, with net power output of 200 kW_E and efficiency of 24.5% (Table 2) for a projected period of 15 years. The cyclic production of rice, rice straws and husks and bioenergy has been done based on material balance (including irrigation land balance) and energy balance.

2.2.1. Cost benefit analysis and profitability evaluation

Profitability of electricity generation from rice straws and husks in a downdraft gasifier has been evaluated using the discounted cash flow criteria [48] and parameters given in Table 2. The financial gains from the use of the bioenergy have been estimated from the difference between the cost of fossil diesel for running the water pumps for irrigation of the rice farms and the cost of bioenergy, which includes labour and transport costs for collection and transportation of the rice straws and husks to a conversion plant.

The financial gains from using bioenergy have been estimated from the cost of fossil diesel that would have been used to run the water pumps for irrigation of the rice farms if bioenergy was not used, labour and transport costs for collection and transportation of the rice straws and husks to a conversion plant.

Financial gain from the use of bioenergy is an estimate from prevailing costs of diesel and selling price of rice at the local market in Malawi using Eq. (3).

$$FS = P_d{*}Q_d + S_p{*}Q_R \tag{3}$$

where:

FS = financial saving from fossil diesel (US$)
P_d = pump price of fossil diesel (US$/litre)
Q_d = quantity of fossil diesel offset by using the bioenergy (kg/litre)
S_p = Selling price of rice (US$/kg)
Q_R = quantity of rice produced from irrigating powered by bioenergy (kg).

Table 2
Factors used in evaluation of cost of generating electricity from rice straws and husks in Karonga district in Malawi using small scale gasifiers.

Parameters[a]	Description	Parameter	value
Gasifier type	Downdraft	Feedstock (500 kg/hour of rice straws and husks at 10–15% mc[b] air dried) (tonnes)	1656
Engine capacity (kW_E) Rated	250.	Feed cost (10–15% mc[b] air dried) per annum (US$)	57364.71
Engine capacity (kW_E) net	200	Feedstock pre-treatment cost per annum (US$)	125326.80
Engine make	Cummins GTA	Utilities cost per annum (US$)	2592.00
Engine model	1710G	Maintenance costs per annum (US$)	18074.11
Electrical efficiency (%)	24.5	Labour cost per annum (US$)	43200.00
Feedstock requirement (kg per hour)	400–500	Total capital cost (US $)	361482.15
Moisture content (%)	10–15	Annual cost of capital (US$)	24098.81
Feedstock particle size (mm)	15–70	Overheads cost per annum (US$)	36148.22
Capital cost (plant cost, civil works, installation and commissioning straws bale presser) (US$)	361 482	Total annual operating cost (US$)	194004.65
		Generation cost of electricity per kWhe[b] (US$)	0.13

[a] Sourced from suppliers of gasifier, web page: – www.radheengineering.com.
[b] Moisture content; [2]kilowatt-hour of the electricity.

2.3. Water requirement for rice production

The net water requirement per hectare for rice production by irrigation has been evaluated from the daily water requirement for rice production for dry planting, including water for evapotranspiration of between 38 and 77 m^3 per day as indicated in literature [49,50]. The size and power rating of the water pump was estimated using Eq. (4) from [51].

$$\text{Power rating of the pump} = P_{h(kW)}/\eta = \left(\frac{Q\rho gH}{3.6x\,10^6}\right)/\eta \tag{4}$$

where

$P_{h(kW)}$ = the hydraulic power in kW.
Q = the flowrate of the water required for irrigation in m^3/h
ρ= density of water in kg/m^3
g = gravitational acceleration in m/s^2
H = total dynamic head (TDH) in m
η = the efficiency of the pump.

The number of hectares that can be irrigated using the bioenergy from the rice straws and husks was estimated using Eq. (5).

$$N = \left(\frac{P_{ER}}{H{*}P_{r(kW)\eta}}\right) \tag{5}$$

where:

N = number of hectares that can be irrigated
P_{ER} = the overall energy generated from the rice straws and husks in TWh
H = Operating hours of the pump (h)

Table 3
Parameters for evaluation of carbon emission and costs benefits of an integrated bioenergy and rice production system.

Parameter	Value
Carbon emission factor of diesel generated electricity[a] (g/kWh)	670
Water required for rice production per hectare[b] (m^3 per day)	59.4
Water pumping rate (m^3 per hour)	3.3
Water pump rated power (kW)	3
Daily water pumping (h)	18
Number of days of water pumping per planting season of rice.	120
Water pump fossil diesel consumption rate (L/ kWh)	0.392
Quantity of fossil diesel required for irrigation per ha (L)	2540
Pump price of fossil diesel in the base year US$/L	1.08
Carbon emission per hectare (tonnes)	4.3
Acreage that can be irrigated using bioenergy in the base year (ha)	2367
Mean rice yield per hectare of dry planting (tonnes)	4.43
Rice selling price in the base year pr kg (US$)	0.65
Total CO_2 emissions offset by bioenergy in the base (tonnes x10^3)	10.18
Financial saving from diesel purchase in base year US$ (x10^6)	6.58
Revenue from excess rice sales in base year US$ (x10^6)	6.82
Cost of chemical fertilizer per ha (US$)	137
Labour cost per ha (US$)	780

[a] Source [52].
[b] Source [48].

$P_{r(kW)}$= the power rating for the pump for irrigating unit area of land in kW.

2.4. Carbon emissions savings

The environmental impacts have been evaluated by assessing the net savings on carbon emissions as a result of utilising electricity generated from the rice straws and husks to run irrigation water pumps instead of fossil diesel (Eq. (6)).

$$\text{Carbon emissions saving} = \frac{N\,(R_p{*}C_f{*}H{*}D)}{1000} \quad (6)$$

where:

N = number of hectares of the rice farms that can be irrigated
R_p= water pump rated power (kW)
C_f = carbon dioxide emission factor of fuel (g/kWh) [53]
H = water pumping hours per day (h/day)
D = days of pumping water into the rice field (day).

The carbon emissions factors were derived from [18,52,53] and are presented in Table 3.

3. Results and discussion

A mean production of 44117 and 6307 t per annum of the rice straws and husks respectively have been estimated from rain fed cultivation of rice farms in Karonga district over the period of 10 years. Collectable portions are estimated at 40% and 65%, respectively. The contextual factors that would influence the use of these bioresources for bioenergy production are discussed in the subsequent sections.

3.1. Contextual factors influencing integration of rice production and bioenergy in Karonga

Karonga district is located in northern part of Malawi between latitude 9°57′S and longitude 33°58′E covering 3355 km^2 with a wet and dry savanna climate. Daily temperature ranges between 30 and 40 °C in dry and hot summer. Total annual rainfall in the district is estimated at about 800 mm (800 l/m^2), received between the months of December and April is conducive for cultivation of rice and other

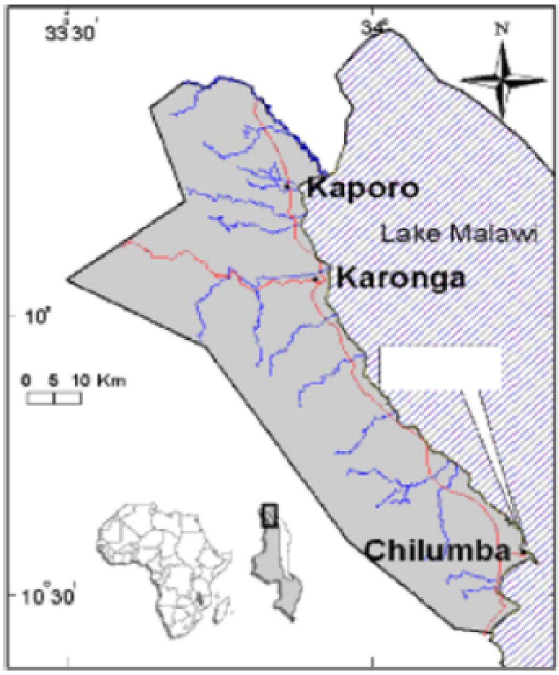

Fig. 1. Rivers and streams flowing from Nyika highlands through Karonga district to Lake Malawi. Source: http://www.lshtm.ac.uk/eph/ide/research/kps/district/ [55] (used with permission from Mia Crampin, Karonga Prevention Study/London School of Hygiene & Tropical Medicine).

crops in the district. The district has a high population density estimated at 80 people per km^2 [54] with a population growth rate of about 2.8% per annum. The high population growth rate is increasing pressure on arable land to meet the food demand. Rice is one of the major crops grown for food and as a cash crop. Rice is predominantly cultivated in low-lying arable land and valleys that are flooded with water from rainfall runoff.

Karonga district is bordered by Nyika highlands to the west and Lake Malawi to the east. The highlands are the source and catchment area of perennial rivers and stream which flow through the district into Lake Malawi (Fig. 1). The deceleration of the water velocities, as the rivers and streams flow through the lowland and the lakeshore into Lake Malawi, provide the opportunity for rice farming during the rainy season. Thus, three rice schemes: Hara, Wovwe and Ngerenge were established by the Government of Malawi (GoM) in early 1980s for rice production in the district. Besides the three rice schemes, rural communities living in the low-lying areas grow rice and other crops for own consumption and for sale. Excess rice that is not needed for own consumption by the rice farming households is sold to the urban population in the district and neighbouring towns at US$0.65 per kilogram.

Irrigation of the rice farms (dry planting) has the potential to increase rice yield per unit area of land per annum through intensive planting per year, which would enhance food security in the district. The Lake Malawi that borders the district to the east provides a secure source of water that can be used for irrigation during dry season. However, such an opportunity has not been exploited.

The lack of energy that can be used to power irrigation pumps is a major limiting factor to promoting dry cultivation of rice in the district. Consequently, rice farming in the area has been restricted to rain fed cultivation. Thus, availability and supply of reliable and secure energy is critical to promote productivity as well as unit operations such as processing and preservation of rice that would reduce postharvest

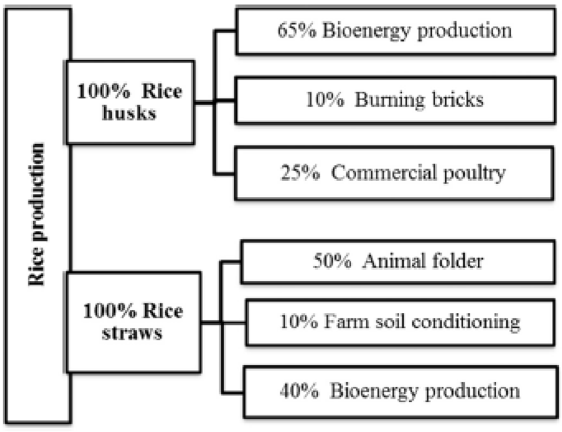

Fig. 2. Potential pathways of utilisation of rice straws and husks in Karonga district.

losses and enhance profitability of the overall rice crop value chain.

In the survey conducted in rice farms and rice mills in the district, it has been observed that the rice straws and husks are poorly managed. The residues are burnt in the field and at the rice processing mills without utilising the released energy. In some cases rice farmers and the communities around the farms graze their livestock in the rice fields after harvesting and before the next planting season. Some rice husks are collected from the rice processing mills for curing bricks and for use in commercial poultry production. The aforementioned uses of rice straws and husks, if not regulated may constitute competing uses that would affect availability for bioenergy production.

Regulations on utilisation of the rice straws and husks have not been established in Malawi. The lack of regulations has the potential to cause variation in the supply chain of rice straws and husks as a result of unpredictable demands on the resources, which in turn may affect feedstock supply for bioenergy production. The potential pathways of the rice straws and husks and corresponding quantities identified and estimated, respectively, through interviews with agricultural experts and the rice farmers at Hara rice scheme are presented in Fig. 2.

3.2. Rice production and availability of rice straws and husks as feedstock for bioenergy production

The availability of bioenergy for irrigation pumping would allow multiple planting of rice, thus, increasing land productivity (rice yield per unit of land per annum) in the farms. Over the period a 10 years (2005–2014), rice production in Karonga district increased from 12533 to 37925 t, representing an increase of 200%. Consequently, the quantities of rice straws and husks in the district correspondingly increased overtime as shown in Fig. 3. The rice straws and husks increased from 22020 and 3346 t in 2005 to 66634 and 10126 t, respectively, in the 10-year period.

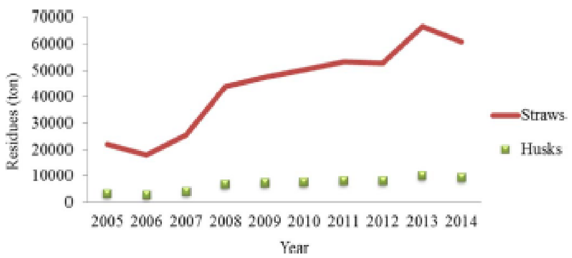

Fig. 3. Trend in a10-year historical rice straws and husks production in Karonga District.

Table 4
Arable land used for rice production and rice yield in Karonga district.

Year	Total Yield (tons)	Land used (ha)	Land not irrigated (ha)	Yield/ha (tons/ha)	Irrigated land (ha)	Yield from irrigated land (tons)	Yield/ha (tons/ha)
2005	12533	8189	8189	1.53			
2006	10284	4714	2644	2.27	1035	4292	4.15
2007	14612	7439	5401	1.90	1019	4344	4.26
2008	25020	10110	8076	2.54	1017	4508	4.43
2009	27093	9718	7558	2.93	1080	4934	4.57
2010	28559	10440	8238	2.86	1101	5045	4.58
2011	30390	11133	8665	2.90	1234	5274	4.27
2012	29973	11661	9233	2.67	1214	5322	4.38
2013	37925	13167	10665	3.00	1251	5880	4.70
2014	34703	13362	10840	2.68	1261	5666	4.49
Mean	25109	9993	7951	2.53	1135	4534	4.43

The increase in rice production over the 10-year period was attributed to the expansion of arable land used for rice production and increase in application of chemical fertilizers. Table 4 shows the arable land used for rice production and rice yield in Karonga district between 2005 and 2014. Land used for rice production increased by 63% between 2005 and 2014, while the government provided chemical fertilisers to farmers in the farm input subsidy programme (FISP) introduced in 2004 [56]. The increase in rice production as a result of expansion of arable land and application of chemical fertilizers may not be feasible in the future. Critical factors that will inhibit this increase include: diminishing suitable arable land resource along the valleys and streams for cultivation of rice that requires flooded water supply, competition for land for infrastructure development to meet the needs of the rapidly growing population at 2.8% per annum in the district, and unsustainability of the short and medium term approach of the chemical fertilizers subsidy programme that was aimed at enhancing food security in Malawi. Multiple cropping of rice promoted by irrigation pumping that is powered by bioenergy from the rice straws and husks produced in the rice farms, can contribute to sustainable increase of both rice (food crop) yield per unit of land and bioenergy production without requiring extra land resource.

About 9.4% of the arable land used for rice production was irrigated in 2014 (Table 4) mainly by gravity fed at Hara and Ngerenge rice schemes. The gravity fed irrigation system is inadequate and limited to specific terrain of the streams and valleys unlike electric powered irrigation systems which can be developed and installed at any location of the rice farms. Owing to lack of energy in the district, about 90% of the rice farms depend solely on wet planting. The results also show that a higher mean rice yield of 4.43 t per hectare was obtained from irrigated land (dry planting) than a yield of and 2.53 t per hectare obtained from the rain fed (wet planting). Therefore, if bioenergy from the rice straws and husks can be targeted to irrigation of the rice farms, it can significantly contribute to increasing rice production by 1.9 t per hectare (75% of the wet planting). The approach has the potential of increasing availability of the rice straws and husks for the bioenergy production system and simultaneously, enhance food security.

3.3. Electricity generation from rice straws and husks

The rice straws and husks that would actually be collected from the rice farms and processing mills for electricity generation, after accounting for the amounts used for competing uses (Fig. 2) could generate about 16.64 GWh in the base year, from the small scale gasification systems that can supply electricity with 95% confidence of supplying the hourly water pumping requirement. The electricity generated could meet about 17% of the energy demand of rural households in the district with average daily energy demand of about 6 kWh per household as per calculations made based on information from literature

[4,52].

3.4. Bioenergy allocation to irrigation of rice farms

The daily water demand of 59.4 m^3 (≈712.8 mm per annum) per hectare is required for the dry planting to promote intensive rice farming in Karonga rice farms. An integrated bioenergy and rice production system can be realised by allocating the bioenergy to irrigation of the rice farms first to increase rice production. About 3.3 m^3 of water per hour pumped for 18 h per day is required to meet the water requirement for rice production per hectare. A water pump rated about 3 kW would require 6480 kWh per hectare to supply the daily water demand in 120 days of rice cropping. In addition, the small scale biomass gasifiers would require about 1656 t (500 kg/h plus a factor of safety of 15%) of feedstock to generate the electricity during the dry planting season. The net amounts of rice straws and husks (26414 t) that would be available in the base year after accounting for competing uses (Fig. 2), would allow installation of about 16 small-scale gasification systems described in Table 2. The energy generated from the gasifiers would power irrigation pumping for 2367 ha of the rice farms in the base year, resulting in an increase of rice production of about 30% (10486 t) (Fig. 4a). The increase in rice production would subsequently increase availability of rice straws and husks for bioenergy production.

Simulation of rice and bioenergy production over a projected 15 year period (Fig. 4a) shows the increase in both rice and bioenergy production as a result of supplying the bioenergy from the rice straws and husks to irrigate the rice farms, in turn increasing the size of the land that could be irrigated. The land irrigated using bioenergy would increase from 2367 to 13537 ha in the 10th cycle of dry planting (Fig. 4a), thus dry planting will cover the same size of land as in wet planting. The rice production would correspondingly increase from 34703 to 59970 t per annum by the 10th year, representing a 73% increase in yield of rain-fed production only, which subsequently, would increase bioenergy generation from the rice straws and husks from 15.34 to 87.72 GWh per annum. If agricultural practices and climate conditions for rice production remained constant, a synergetic integration of bioenergy and rice production can significantly contribute to double cropping, increasing both rice (food crop) and bioenergy production in the rice farms in Karonga district.

Table 5
Comparison of rice production from three sources of water supply.

Scenario	*Basd case – Rain fed* Rain fed +9.3% of land irrigated by gravity.	*Fossil fuel irrigated* Rain fed +100% Fossil fuels powered irrigation.	*Bioenergy irrigated* Rain fed +100% Bioenegy powered irrigation.
Land – Rain fed (ha)	13362	13362	13362
Mean Yield/ha – Rain fed (ton/ha)	2.53	2.53	2.53
Irrigated land (ha)	1261	13362	13362
Mean Yield/ha – irrigated land (ton/ha)	4.43	4.43	4.43
Potential mean rice yield/ annum (ton)	39392.09	92999	92999

A comparison of the extensive rice farming (extensive agriculture) or change of land use that depends on rain-fed production, based on the rice yield per hectare from rain-fed cultivation presented in Table 4 and the intensive rice farming using bioenergy for irrigation of the rice farms in Fig. 4 indicates that 23704 ha would be required or would be taken away from production of other crops to produce the rice to the same amount as obtained in the 10th cycle of allocating the bioenergy to irrigation of the rice farms. Thus, allocation of bioenergy, produced from the rice straws and husks, to irrigation of the rice farms can reduce competition for land utilised for production of other crops while increasing availability of rice and the feedstocks for bioenergy production. Table 5 provides current and potential scenarios of rice production: (i) base case, the existing scenario in the district of rain fed rice production with only 9.3% of the land irrigated using gravity fed irrigation system, (ii) rain fed and 100% of the land irrigated using

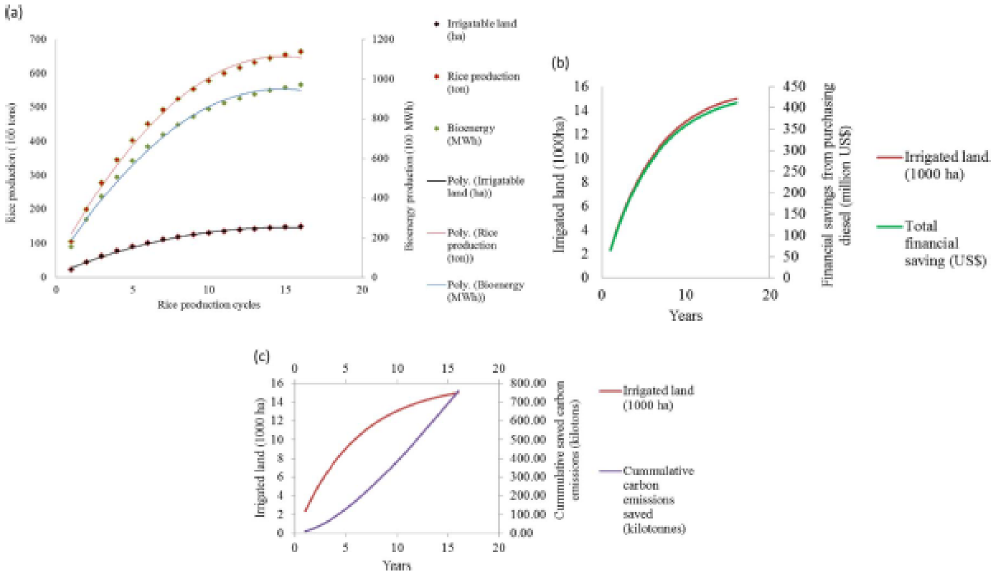

Fig. 4. Increase (a) in rice and bioenergy production and irrigatable land in a synergitic integrated bioenergy system over a projected period of 15 years. Equations $y=-276.01x^2 +8142.5x +4993.9$, $y=-403.73x^2 +11910x +7304.8$ and $y=-62.305x^2 +1838x +1127.3$ are trendlines for rice production, bioenergy production and irrigatable land. All equations have R^2 of over 0.995, (b) Financial savings from purchase of diesel for irrigation of the rice farms and (c) Carbon emissions saved from using diesel for irrigation of rice farms.

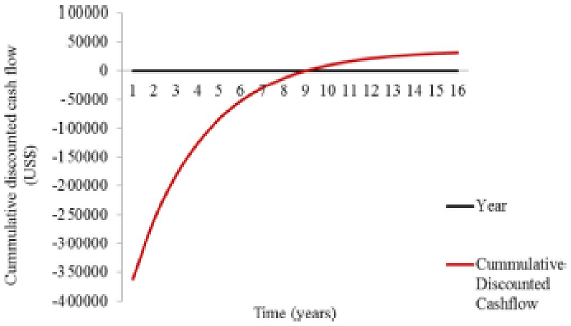

Fig. 5. Cumulative discounted cash flow for the electricity from rice straws and husks at selling price of US$0.166 per kilowatt-hour.

fossil fuels, and (iii) rain fed with about 100% of the land irrigated using bioenergy.

3.5. Cost and benefit analysis and profitability evaluation of generating and using self-generated bioenergy in rice farms

Electricity generated from the rice straws and husks in the 250 kW_E downdraft gasifiers would cost about US0.13 per kWh. Key elements used in calculation of the cost of electricity are presented in Table 3. Although the collection of residues from the farms and processing plants would be considered free of charge, the labour costs incurred in baling of the straws and comminution and transportation contribute significantly to the cost of feedstock and the cost of generating the electricity. Discounted cash flow evaluation of investment in electricity generation from the rice straws and husks using the small-scale gasification systems shown in Fig. 5 shows that, at lending rate of 35%, offered by financing institutions in Malawi at the time of the study, would breakeven in the 8th year at electricity selling price of US $0.166 per kilowatt-hour of the electricity. However, the price is higher than the average subsidised price of electricity from hydro in Malawi (US$0.094 per kilowatt-hour). A fiscal policy that can support reducing the cost of investment in the bioenergy technologies can increase the competiveness of electricity from the bioenergy systems with the subsidised grid electricity from hydro systems in Malawi.

Rice production would increase by investing in water pumps powered by diesel or grid electricity. In the base year, 6040 kilolitres of diesel would be required to run the pumps for irrigation of the same amount of land as irrigated by pumps powered by electricity from rice straws and husks.

About 10.28 kilotonnes of CO_2 would be emitted from the diesel pumps, which would contribute to carbon footprint of 0.98 kg CO_2/kg of rice. It can be observed in Table 6 that the total annual operational

Table 6
Total annual operational costs and of gasification of rice straws and husks system and fossil diesel powered systems of similar power output for irrigation of the rice farms.

	Rice straws and husks gasifier	Diesel water pumps	Diesel generator
Energy yield (kWh)	16.64×10^6	16.64×10^6	16.64×10^6
Capital costs (US$)	361482.15	–	–
Feedstock (fuel) cost (US$)	57365	64936563	158957
Irrigated area in base year (ha)	2367	2367	2367
Total annual operating costs (US$)	194005	6505803	224838
Cost of energy (COE) (US $/kWh)	0.13	0.42	0.15

costs of diesel water pumps amount to US$6505803 to irrigate the same amount of land as irrigated by pumps powered by electricity from rice straws and husks in the base year compared to US$194005 for the gasification system and US$224838 for diesel generator. Thus, using the straws and husks for onsite generation of electricity for irrigation pumping of the rice farms has multiple environmental and economic benefits to the rice farmers in the district.

Although rice production would also be increased by investing in water pumps powered by fossil fuels or grid electricity (Table 6), major limitations include the volatility in supply and prices of fossil fuels combined with inadequate electricity generation capacity in Malawi. The cost of the generating electricity from diesel is higher than gasification system as a result of the inherently high operational costs attributed mainly to the cost of acquiring and distributing the diesel. Volatility in supply and prices of fossil fuels are eminent challenges in Malawi, which result in fuel supply uncertainty, consequently, increasing financial burden on the farmers. In contrast, farmers will have some level of control of the cost of acquiring and processing the rice residues into bioenergy in the value chain because of the duo role they have, as feedstock suppliers and as the end users of the bioenergy.

Bioenergy from rice straws and husks used for irrigation of the rice farms would enable rice farmers save up to US$6.58 million in the base year of irrigating 2367 ha, from buying fossil diesel besides maintenance costs of the diesel water pumps. In the 15th year of the bioenergy systems, farmers would save more than US$223.28 million when the cost of fossil diesel is accounted for (Fig. 4b).

The increase in rice production would also increase gross income to the farmers of about US$6.82 million from sales of the rice from dry planting using the bioenergy in the base year. The gross income would cumulatively increase to US$253.31 million by the fifteenth year (Fig. 4b). Key expenditures incurred by the rice farmers on inputs and labour were estimated at about US$137 and US$780 per hectare respectively. Thus, the farmers would gain a net income of about US $4.65million from sales of the rice from dry planting of 2367 ha in the base year and US$172.64 million in the fifteenth year (Fig. 4b). The total financial gain from savings from purchase of diesel and from sales of the rice from dry planting would be US$179.81 million in the fifteenth year of targeted supply of bioenergy to irrigation of the rice farms (Fig. 4b). Thus, the synergetic integration of bioenergy and rice production approach has the potential to increase both food and bioenergy production with multiple environmental and socioeconomic benefits to the farmers.

3.6. Integrated bioenergy and rice production system

Rice farming in Karonga district is constrained to low-lying arable land along the valleys that receive adequate water supply from both rainfall and runoff from upland areas. Intensive and extensive rice farming, including change of land use for rice production, require intensive input of energy for water pumping for irrigation of the farms to meet the daily water requirement of the rice crop. The results presented in Sections 3.2 and 3.3, indicate that in the base year about 18.3 GWh_E would be generated from the straws and husks that can realistically be collected from the rice farms and processing mills, after accounting for the straws and husks that are collected for other uses. The bioenergy from rice straws and husks from wet planting of the rice would provide the initial input energy in the base year for irrigation of 2367 ha of the rice farms for dry planting, thus allowing double cropping per hectare per annum which would increase the rice yield per hectare per annum. The results in Fig. 4a show that increasing rice yield per hectare per annum in the rice farms through irrigation would increase the amount of the rice straws and husk that would be available for bioenergy production that is synergistically integrated with rice production.

Promotion of off-season rice irrigation enhances intensive land use and increase rice yield per unit of land per annum. The approach can be

Table 7
Suggested approaches to integrating bioenergy in agriculture in Malawi.

	Approach	Objective
1	Intensive agriculture	Produce more food crop per unit area of land than food requirement and use the surplus yield for bioenergy production.
2	Extensive agriculture	Open more arable land (expansion of cultivated arable land) to produce more food crop than food requirement and use the excess yield for bioenergy production.
3	Change in land use	Make bioenergy crops more economical with better prices than current cash crops in the area/region to motivate farmers to cultivate energy crops
4	use of crop residues	Utilise wastes for bioenergy production

augmented by other practices such as the use of high yield rice varieties and reduction of post-harvest losses to raise the yield ceiling per cropping season per unit area of land [57–59], thus, increasing the rice production and food availability without seeking for extra land resource. Furthermore, the approach can advance integration of agriculture and bioenergy production systems in other agricultural systems as presented in Table 7 [60]. In the absence of intensive input of energy for pumping water for irrigation of the rice farms, the water requirement for the production of rice is a critical limitation to multiple cropping (intensive rice farming), the expansion of arable land (extensive rice farming) and land that can be freed from other crops (change of land use) for rice production.

A schematic flow of an integrated rice and bioenergy production system that would prevail at the rice farms in a looped process design is shown Fig. 6. The rice from dry planting using the gravity fed irrigation is harvested in November just before the start of the rainy season. In a normal rainy season with estimated precipitation of about 800 mm, irrigation is least required in the district. In addition, animal folder is provided from green pasture and moulding and curing of bricks is suspended during the rainy season. Only 10% of the straws and 25% of the husks from dry planting used for soil conditioning and commercial poultry respectively (Fig. 2), would not be available for bioenergy production. As a result, the straws and husks produced from dry planting could be combined with those produced from the wet planting, increasing and promoting sustainable supply of feedstock for bioenergy to be used in the next dry planting.

Alternatively bioenergy could be produced during the rainy season to supply to about 200 households for home use and other productive farming activities such as post-harvest processing of the rice and residues generated during wet planting. Excess energy, not required for irrigation could also be used to reduce labour bottlenecks for rice management, which would reduce the varience between actual and expected feedstock yield [55]. Agricultural residues from the other crops grown in the district , can provide supplementary feedstock to the rice straws and husks to enhance the boenergy system availability and reliability of energy supply.

Women constitute about 60% of the prime labour in the rice farms. However, women are also responsible for collection of fuelwood for household energy needs. Thus, bioenergy can have multiple benefits of

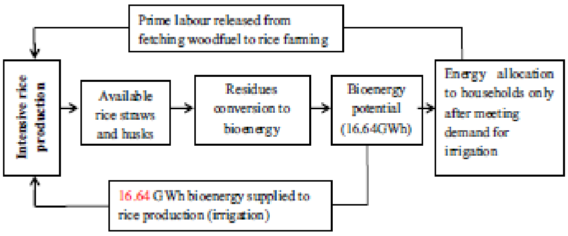

Fig. 6. Integrated rice and bioenergy production systems flow diagram.

reducing the burden of fetching for firewood on women thereby allowing the prime labour to concentrate on rice production with the potential of improving management of the rice farms and increasing rice production.

3.7. Environmental benefits of the rice straws and husks bioenergy value chain

Bioenergy production from the rice straws and husks in the rice farms in Karonga district would reduce the potential fire risk from the husks that accumulate in piles at the rice processing mills. It would also reduce emission of methane gas from gradual biodegradation of the rice straws that are not utilised in the farms and the husks at the rice processing mills. Thus, promoting sustainable disposal and improving the aesthetic of the environment around the mills. Furthermore, the bioenergy would offset fossil fuels that would have been used for irrigation of the rice farms to obtain similar increase in rice production. The use of fossil fuels has both local and global environmental effects from greenhouse gas emission. Evaluation of carbon emissions from fossil diesel that would have been used for irrigation of the 2367 ha of the rice farms indicates that about 8.82 kilotonnes of CO_2 would have been emitted in the base year (Fig. 4c). An integrated bioenergy and rice production supplying the bioenergy to irrigation of the rice farms would cumulatively offset about 285.33 kilotonnes of CO_2 in the projected period of fifteen years of the lifespan of the bioenergy conversion plant (Fig. 4c).

4. Conclusion

The rice straws and husks that are produced annually in the rice farms and rice processing mills in Karonga district in Malawi can be utilised to enhance both bioenergy production and rice production systems without taking away land from cultivation of other crops. The approach has shown potential to enhance incremental investment and deployment of modular decentralised small-scale bioenergy and irrigation systems in the rice farms when more straws and husks are produced from dry planting. Therefore, enhancing food crop productivity per unit of land and food security when adopted and implemented in the rural agricultural sector in Malawi. Strategically targeted bioenergy production in rice production would enable diffusion of bioenergy technologies in Karonga district with potential for adoption in other districts in Malawi and beyond where rice is also grown.

Bioenergy from the residues supplied to irrigation of the rice farms has environmental benefit of offsetting carbon emissions from fossil diesel which would have been used to irrigate the farms if bioenergy was not used, and reducing the fire risks at the rice processing mills. The direct economic benefits of the approach to the rice farmers include financial savings from purchasing the fossil diesel for irrigating, and additional revenue from sales of excess rice produced from dry planting as a result of using the bioenergy. Thus, the synergetic integration of bioenergy and rice production, using the rice straws and husks, provides a bioenergy/food nexus with the potential to enhance food security and sustainable energy supply simultaneously, with environmental and economic benefits in the rural rice farming communities in Karonga district in Malawi. Realisation of this potential will depend on improving the handling, management and processing of the bioresourcre and formulation of regulations to synchronise the use of rice strwas and husks for bioenergy production and competing uses such as straws for soil conditioning and folder for livestock, and husks for commercial poultry and curing of bricks for construction.

5. Recommendations

In order to improve management and utilisation of the rice straws and husks for bioenergy production and other socioeconomic uses, policy and regulations have to be formulated to address potential variability in the rice straws and husks value chain, which may arise from competing uses of the residues.

A full life cycle assessment of developing the rice straws and husks value chain will have to be carried out to investigate the effects on soil leaching which may result from intensive use of rice farms due to multiple cropping per year when irrigation is implemented.

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Appendix A2: Abstracts of papers presented at conferences

A2.1: A systems approach model for sustainable production of bioenergy from primary forest residues from Viphya plantations in Malawi

12. Systems approach model for sustainable production of bioenergy from primary forest residues from Viphya plantations in Malawi

Maxon L. Chitawo[1], Annie F.A. Chimphango[2], Steven.O. Peterson[3]

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E-mail: maxonchitawo@yahoo.co.uk, achimpha@sun.ac.za
[3]Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, USA
E-mail: Steven.O.Peterson@dartmouth.edu

INTRODUCTION

Provision of sustainable energy, especially to the rural and semi urban households, is one of the main challenges facing development of the energy sector in Malawi. About 98% of the rural and semi urban households rely on fuelwood for most of the energy needs (Zalengera et al., 2014). Households collect fuelwood from indigenous forests and use it in inefficient cook stoves. Despite the challenges besting the bioenergy sector, Malawi is endowed with other potential bioresources, such as primary forest residues produced from logging and sawmilling in forest plantations. The residues can be utilised for bioenergy production. However, significant amounts of primary forest residues are left in the plantations and are underutilised. The Viphya forest plantations located in Mzimba and Nkhata Bay districts in northern Malawi, which has been in the first cycle of harvesting for timber production since 2001, is are the single largest block of forest plantations covering 53501 hectares of predominantly pine trees. Primary forest residues produced from logging and sawmilling processes in the plantations can be utilised for production of modern forms of energy (bioenergy) such as electricity, which can be supplied to rural communities around the plantations.

Although bioenergy from primary forest residues is renewable energy, it is produced as a by-product of the timber industries (Bolkesjø et al., 2006). Consequently, production and supply of bioenergy is proportional to production of timber. An initial exploitation of mature stands in plantations developed for timber production will change the forest age structure, which in turn can have implications for long-term sustained harvest, and this has implications for investment in bioenergy production and supply.

The harvesting methods, site characteristics, logging and sawmilling technologies, and sawyer (operator) capability to operate the technologies have been identified as influencing factors to the amount of residues generated in forest plantations (2014; Eshun et al., 2010) which in turn influence how rapidly a mature forest stand can be exploited. Sustainable production of bioenergy from primary forest residues from Viphya forest plantations is complex multifaceted problem that concerns governance, technical, environmental, economic and social issues. Understanding and improving the sustainability of this complex system requires a holistic approach that considers accumulations, flows, and feedbacks within the real system. This study is using systems approach to map the primary forest residues supply chain from Viphya forest plantations in northern Malawi and develop a model for sustainable production of bioenergy. The approach is based on systems thinking/system dynamics (SD) modelling methodology (Forrester, 1992), which has been applied in the sustainability assessment of technology for bioenergy production (Musango and Brent, 2011).

The study undertakes the first step in a more comprehensive model of a bioenergy system utilising primary forest residues from Viphya forest plantations for feedstock. The model presented in this paper focuses on stand dynamics within the forest plantations. This provides a physical "anchor" for the comprehensive model. The study contributes to development of an integrated forest plantations management and bioenergy production framework for sustainable harvesting and replanting of the Viphya forest plantations that can promote steady flow of both timber and primary forest residues.

METHODS

Qualitative and quantitative data sets were collected in a survey conducted with the stakeholders from the forestry and energy sectors in Malawi using group discussions, semi structured and structured questionnaires. Data on timber throughput, harvesting technologies and residues generation fractions (rgf) was obtained from plantations management reports and from interviews with the sawyers. Onsite inventory on use of Wood-Miser sawmilling technology in the plantation was carried out on one hectare of harvested mature forest stand to validate the data on residues yield per hectare obtained from management reports. The modelling of sustainable production of bioenergy from primary forest residues from Viphya plantations involved use of the first four of the six key steps developed by Forrester for effective modelling in system dynamics (Forrester, 1992), presented in Figure 1. Both qualitative and quantitative data sets were used in the development of the dynamic hypothesis and the stock and flow diagram of the harvesting and replanting sub model presented in Figures 2 and 3 respectively.

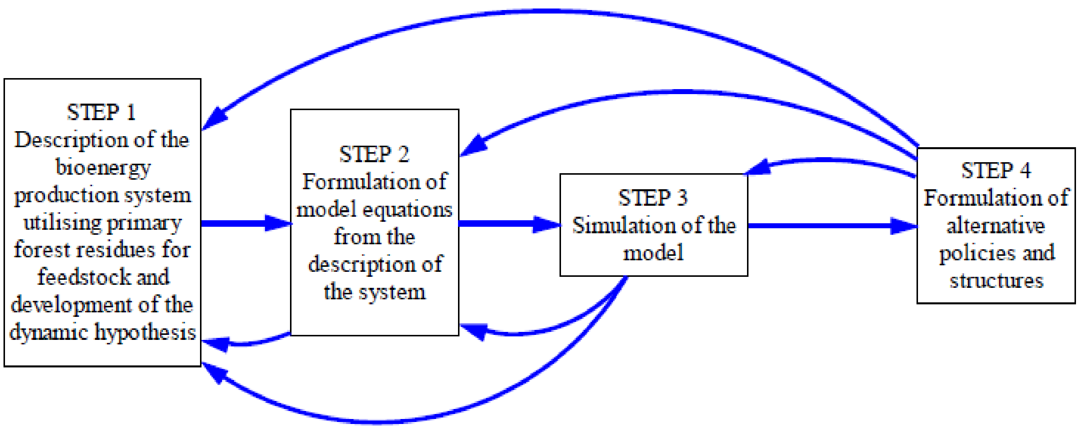

Figure 1: Key steps in modelling bioenergy production from primary forest residues from Viphya forest plantations. Adapted and redrawn from Forrester, (1992).

The key feedback structures in the Viphya forest plantations management are presented using the causal loop diagrams in Figure 2. The harvesting loop indicates that harvesting of mature stand decreases the net mature stand available in the plantations. The plantations have a limited capacity of 33501 ha where small and medium scale sawyers harvest the mature stand for timber production, which decreases the mature stand harvest per sawyer overtime. On the hand, harvesting of mature stand increases the area for replanting that increases replanting requirement, which after a delay in replanting, increases young stand in the plantations

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that increases maturing stand that mature after 25 years thereby increasing the net mature stand in the plantations.

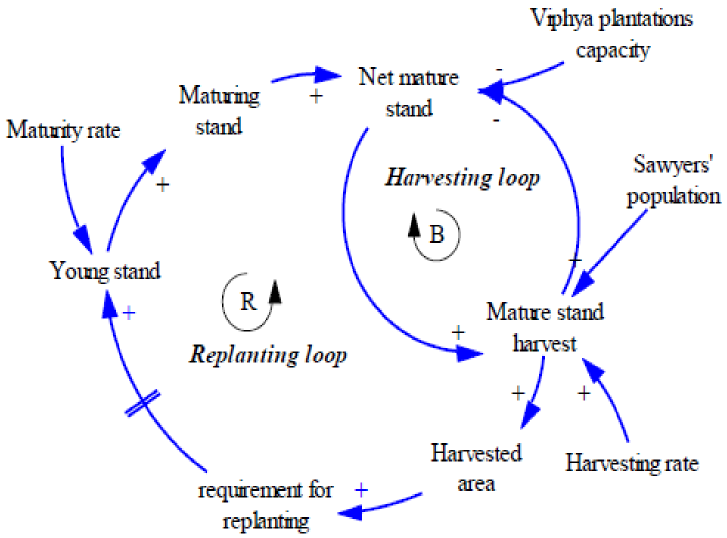

Figure 2: Key feedback structures in replanting and harvesting of the Viphya forest plantations.

The stock and flow diagram in Figure 3 captures forest stand dynamics for Vipya plantations. Each of the five stages of immature forest stock represents the amount of land in its respective class. Given that the pine tree species planted in the plantations have maturation time of 25 years, land spends on average, 5 years in each of the immature forest stages. The only removal of land from forestry is associated with recently harvested land. Land is assumed to remain for 2 years in a recently harvested state, from which some fraction (40 %) is replanted and the remainder is removed from the system (remains in bare state after harvesting).

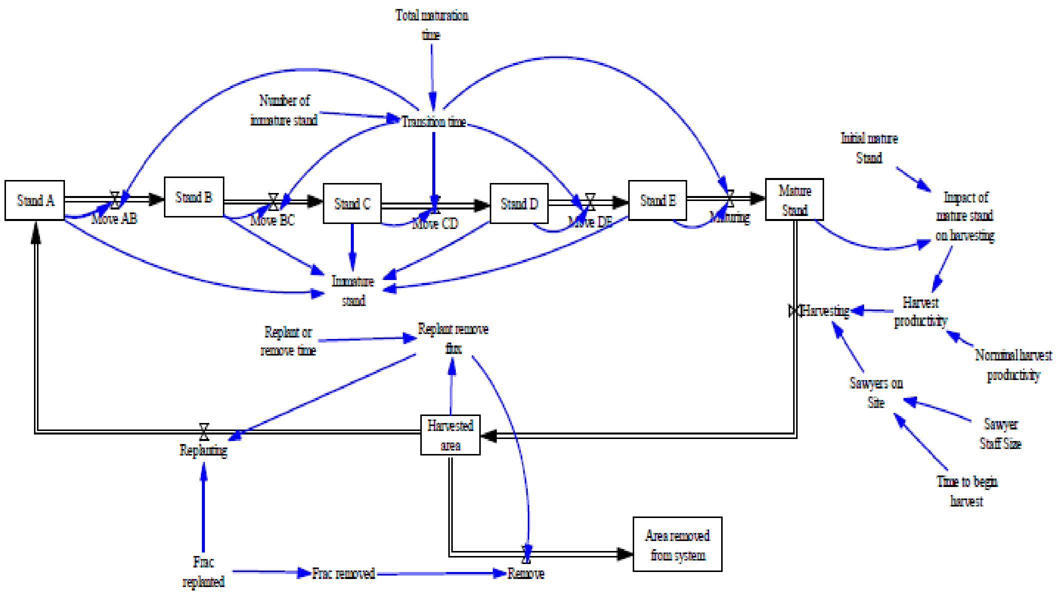

Figure 3: Stocks and flows diagram of harvesting and replanting sub model of the Viphya forest plantations as source of primary forest residues

RESULTS

Harvesting of mature forest stand in the 33501-ha section of the Viphya forest plantations is carried out by small-scale sawyers using mobile sawmilling technologies. Figure 3a shows the variation in mature stand harvested at annual rates of 6.28 and 12 ha per sawyer represented by the base case and over exploitation of the mature stand in the plantations while only 40% of the harvested area is replanted after a delay.

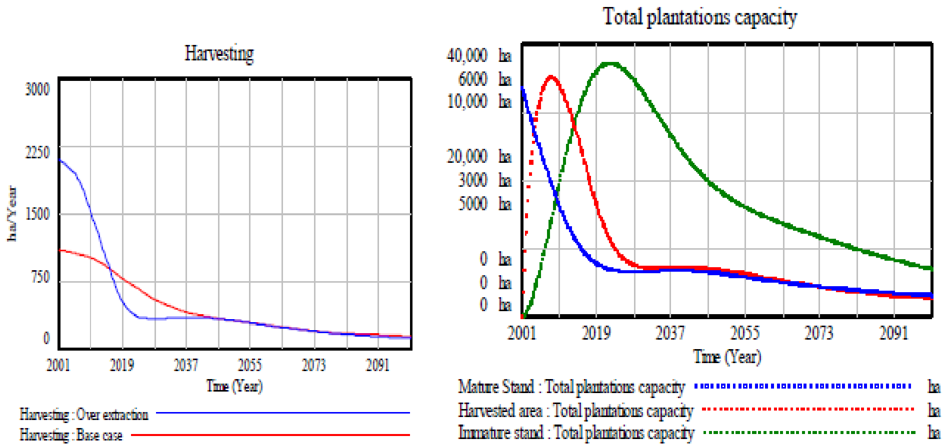

Figure 3: The effect of mismatch in replanting and harvesting of mature stand on availability of mature stand for timber production over time. (a - left) Variation in mature stand harvesting at 6.28 and 12 ha per sawyer per annum while replanting 40% of harvested area; (b - right) mature stand, harvested area and immature stand at 12 ha per sawyer per annum harvesting rate

The over exploitation of mature forest stand scenario shows that the increase in harvesting of mature stand and the partial replanting of the harvested area result in sharp decrease in mature stand in the plantations over time. Subsequently, the increase in harvesting of mature stand increases the area that needs replanting in the plantations (Figure 3b). The decrease in mature stand in the plantations causes the decline in harvesting that decreases the harvested area over time while as the increase in immature stand is a consequence of harvesting that is changing the age structure of the plantation. Thus, both timber and primary forest residues production would decrease with decreasing availability of mature stand in the plantations owing to the proportional dependency of primary forest residues production and availability on timber production. Availability of primary forest residues for bioenergy production would be undermined significantly in the over-exploitation case. The decrease in residues production over time would exacerbate sustainability challenges of bioenergy production and allocation to end users.

In addition, partial replanting of the harvested area leaves some land out of the system over time, which lowers the potential to generate trees in the plantations. An integrated forest plantations management and bioenergy production framework to promote synchronised harvesting of mature stand and replanting of the harvested area can support continuous and stable availability of mature stand in the plantations, which in turn would promote steady production of primary forest residues. Figure 4 shows the scenario of replanting the total area harvested per annum in the same period when the annual allowable cut (AAC) is equal to minimum replanted area per annum. The results in Figure 4 indicate that a stable availability of mature stand, immature stand and harvesting of mature stand over time can be achieved when 100% of the harvested area is replanted in the same year. Stable availability of mature stand can promote sustained production and supply of primary forest residues for bioenergy production.

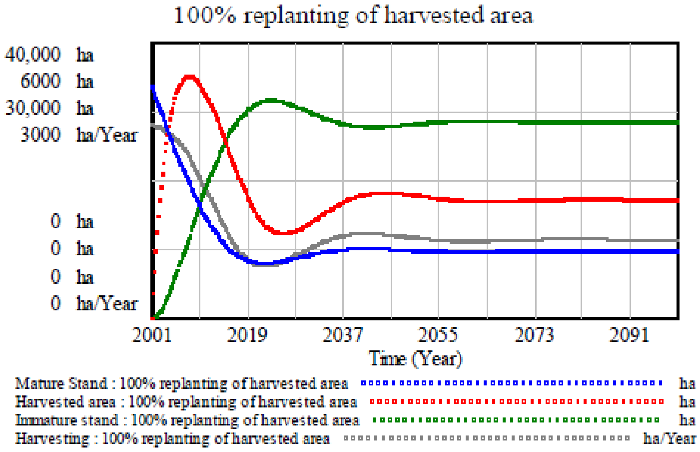

Figure 4: Availability of mature stand, immature stand and harvesting of mature stand over time when 100% of the harvested area is replanted in the same year.

CONCLUSIONS

Forest plantation stand management is critical to steady flow of residues. In particular, rapid exploitation will lead to overshoot in availability of residues, and the design challenge is to manage both the outflow and the "supply chain" for trees. An annual allowable cut (AAC) of the mature stand followed by replanting of total area harvested per annum can promote reliability of timber, primary forest residues and bioenergy production and supply to end users. Dynamic modelling of residues utilisation, bioenergy production and supply and testing of the framework to determine its feasibility of attaining the desired state of the system will have to be developed further in this work, which is in progress.

Keywords: Primary forest residues, sustainable bioenergy production, Viphya plantations, systems approach, Malawi, rural households.

Acknowledgment: The authors would like to express appreciation for the support of the Department of Process Engineering of Stellenbosch University, the Government of Malawi, National Research Foundation (NRF) of South Africa, National Commission for Science and Technology (NCST) in Malawi.

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Zalengera C., Blanchard R.E., Eames P.C., Juma A.M., Chitawo M.L., Gondwe K.T. 2014. *Overview of the Malawi energy situation and A PESTLE analysis for sustainable development of renewable energy*. Renewable and Sustainable Energy Reviews, 38 p335-347. www.elsevier.com/locate/rser.

A2.2: A systems approach mapping of primary forest residues for sustainable production of bioenergy in Malawi

conferenceseries.com

Maxon L Chitawo et al., J Fundam Renewable Energy App 2016, 6:5(Suppl)
http://dx.doi.org/10.4172/2090-4541.C1.017

2nd International Congress and Expo on
Biofuels & Bioenergy
August 29-31, 2016 Sao Paulo, Brazil

A systems approach mapping of primary forest residues supply chain for sustainable production of bioenergy in Malawi

Maxon L Chitawo and **Annie F A Chimphango**
Stellenbosch University, South Africa

Variations overtime in the supply chain of primary forest residues have the potential to exacerbate sustainability challenges in bioenergy production from the residues. Understanding the sources and causes of these variations along the supply chain can enable formulation of policy frameworks that can enhance availability and steady supply of the residues for sustainable production of bioenergy. This paper presents a systems approach mapping of primary forest residues supply chain from Viphya forest plantations in northern Malawi to elucidate potential sources of variations overtime in the residues supply chain. Management and harvesting systems and technologies applied in the plantations, residues production, post harvesting handling and utilisation were assessed from plantations management reports and from onsite material balance of timber production processes. Over extraction of mature stand, delayed replanting, coupled with high death rate of replanted trees resulted in depletion of the plantations in 15 years before maturity age (25 years) of first set of replanted trees, which in turn led to intermittent supply of the residues. Key sustainability challenges along the supply chain categorised as managerial, economic, environmental, social and technical logistics are presented in the paper. Stakeholder analysis along the supply chain revealed the power/influence, interests and concerns of the stakeholders in the value chain that provide opportunities for management innovations in the supply chain for sustainable production of bioenergy from the residues. An integrated forest plantations management and bioenergy production framework can allow sustainable harvesting of mature stand for timber and bioenergy production from primary forest residues from Viphya plantations.

Biography

Maxon L Chitawo is a PhD student at Stellenbosch University in the Process Engineering department. He comes from Malawi, where he is an Academic Member of Staff at Mzuzu University in the Department of Energy Studies where he also Heads the Bioenergy Systems Research Group. He did his Bachelor's degree in Mechanical Engineering at The Polytechnic, University of Malawi from 1991 to 1996 and Master's degree in Renewable Energy Systems Technology at Loughborough University in United Kingdom from 2006 to 2007. His research interest is in bioenergy systems focussing on sustainability issues.

18896790@sun.ac.za

Notes:

Appendix A3: Research Ethics Consent

A3.1: Stellenbosch University Research Ethics Committee Approval

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot · your knowledge partner

Approval Notice
Response to Modifications- (New Application)

18-Feb-2015
Chitawo, Maxon ML

Proposal #: HS1148/2014
Title: Systems approach in developing a model for sustainable production of bioenergy in Malawi.

Dear Mr Maxon Chitawo,

Your **Response to Modifications -** ***(New Application)*** received on , was reviewed by members of the **Research Ethics Committee: Human Research (Humanities)** via Expedited review procedures on **21-Jan-2015** and was approved.
Please note the following information about your approved research proposal:

Proposal Approval Period: **21-Jan-2015 -20-Jan-2016**

Please take note of the general Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

Please remember to use your **proposal number** (**HS1148/2014**) on any documents or correspondence with the REC concerning your research proposal.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Also note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required. The Committee will then consider the continuation of the project for a further year (if necessary).

This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki and the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health). Annually a number of projects may be selected randomly for an external audit.

National Health Research Ethics Committee (NHREC) registration number REC-050411-032.

We wish you the best as you conduct your research.

If you have any questions or need further help, please contact the REC office at .

Included Documents:
Questionnaire
REVISED_Response to Modifications
Informed consent form
REVISED_Questionnaire_RAIPLY
REVISED_Questionnaire_SMFEs
Research proposal
Ethics clearance_NCST
REVISED_Questionnaire_Forest Office North
REC application form
REVISED_REC application form

REVISED_Questionnaire_Ministry of Agriculture
REVISED_Questionnaire_DOE
REVISED_Questionnaire_Forest Office Viphya
Permission letter_DOE
REVISED_Questionnaire_Forestry
(REC COORDINATOR NOT DEFINED - CONTACT MODULE ADMINISTRATOR)

Clarissa Graham

DIE UNIVERSITEIT VAN STELLENBOSCH
18 FEB 2015
THE UNIVERSITY OF STELLENBOSCH

A3.2: Research Ethics Clearance: National Commission for Science and Technology

NATIONAL COMMISSION FOR SCIENCE & TECHNOLOGY

Lingadzi House
Robert Mugabe Crescent
P/Bag B303
City Centre
Lilongwe

Tel: +265 1 771 550
+265 1 774 189
+265 1 774 869
Fax: +265 1772 431
Email:directorgeneral@ncst.mw
Website:http://www.ncst.mw

All communication should be directed to the Director General

Ref No: NCST/RTT/2/6 **16 February 2015**

Maxon Lexon Chitawo
Process Engineering Department
Stellenbosch University
Private Bag X1
Matieland 7602, South Africa

Dear Maxon Chitawo,

RESEARCH ETHICS APPROVAL OF PROTOCOL P01/15/26: SUSTAINABLE PRODUCTION OF BIOENERGY FROM LOCALLY AVAILABLE BIOMAS RESOURCES IN MALAWI

The National Committee on Research in the Social Sciences and Humanities (NCRSH) reviewed your protocol and granted ethical approval. This approval is valid for one year from the date of issuance of this letter. If the study goes beyond one year, an annual approval for continuation shall be required to be sought from NCRSH.

As per stipulated regulatory requirements that appear on the checklist of application, you are required to pay a fee of 10% of the research budget as indicated in your research proposal being a compliance and capacity building fee. **This fee is required to be paid promptly to the Commission before implementation of your study**.

Wishing you successful implementation of your study.

Yours Sincerely

Martina Chimzimu
NCRSH ADMINISTRATOR AND RESEARCH OFFICER
HEALTH, SOCIAL SCIENCES AND HUMANITIES
For: CHAIRMAN OF NCRSH

A nation with scientifically and technologically led sustainable growth and development

A3.3: Letter of approval from Ministry of Agriculture, Irrigation & Water Development

Telephone: 1789 033
Telefax: 1 789 218
Fax: 1789 216

UNITY AND FREEDOM

MINISTRY OF AGRICULTURE,
IRRIGATION AND WATER
DEVELOPMET
P.O. BOX 30134,
CAPITAL CITY,
LILONGWE 3,
MALAWI.

Ref. No. 30/1/1

16th April, 2015

Mr. Maxon Lexon Chitawo,
Process Engineering Department,
Stellenbosch University,
Private Bag X1,
Matieland 7602,
South Africa.

Dear Sir,

RE : REQUEST FOR PERMISSION TO INTERVIEW AND HOLD DISCUSSIONS WITH OFFICERS IN THE MINISTRY ON SUSTAINABLE PRODUCTION OF BIOENERGY IN MALAWI

Reference is made to your letter dated 19th January, 2015 regarding the above captioned subject matter.

I am pleased to inform you that approval has been granted for you to interview members of staff in the Ministry as part of your data collection for your PhD research. In this regard, I also wish to request that you share your questionnaire for the Ministry's information.

Yours faithfully,

McCallum M. M. Sibande
for: **SECRETARY FOR AGRICULTURE, IRRIGATION AND WATER DEVLOPMENT**

A3.4: Letter of approval from Department of Energy Affairs

Fax: (265) 1 771954/770094
Telephone: (265) 1 770688/1 770936
Email: doenergy@malawi.net
All correspondences to be addressed to:
The Director of Energy Affairs

UNITY AND FREEDOM

In reply quote Ref. No.DoE/1/3/12
DEPARTMENT OF ENERGY AFFAIRS
PRIVATE BAGS 309
LILONGWE 3
MALAWI

Ref. DOE/1/3/12 — 10th December, 2014

Mr. Maxon Chitawo,
Stellenbosch University,
Private Bag X1,
Matieland 7602
SOUTH AFRICA.

PERMISSION TO INTERVIEW AND HOLD DISCUSSIONS WITH OFFICERS IN THE DEPARTMENT OF ENERGY AFFAIRS

Reference is made to your request for permission to interview and hold discussions with officers in the Department of Energy Affairs as part of data collection for your research on systems approach in developing a model for sustainable production of bioenergy in Malawi.

I am pleased to inform you that the Department of Energy Affairs has granted you permission to conduct interviews and hold discussions with officers in the Department relating to your research. Please let us know when you intend to meet the officers.

We wish you well in your research.

Joseph Kalowekamo
For: **DIRECTOR OF ENERGY AFFAIRS**

1

A3.5: Permission from Mzimba District Council to conduct research at Elamuleni rural community in the district

From: Thomas Chirwa <tewchirwa@yahoo.co.uk>
To: maxonchitawo@yahoo.co.uk tewchirwa6@gmail.com
28/02/15 at 6:29 AM
Dear Sir,

Permission is granted! My office will write a letter to the Chief informing him of your coming and what you want to do. You will carry this letter together with that from your institution to him as evidence that you are a student/scholar who wants the information for academic purposes

I assure you of our support throughout your exercise including coming in where communities prove to be resistant

Good day

****
Thomas Chirwa
District Commissioner
M'mbelwa District Council
P.O. Box 132
Mzimba

Tel (O).: +265 1 342 255
(H).: +265 1 311 838

Mobile #s.: +265 999 318 646
: +265 888 691 424
E~mail: tewchirwa6@gmail.com;:tewchirwa@yahoo.co.uk

From Maxon Chitawo <maxonchitawo@yahoo.co.uk>
To Thomas Chirwa
09/03/15 at 3:15 PM
Dear Sir

Following our previous communication, I have identified a Community at Elamuleni area to conduct community energy appraisal and household energy survey. As you had indicated Sir that you would assist me with a letter to the TA and traditional leaders of the community, I would appreciate if you assisted me with the letter so that I carry with me to the community, Sir. My plan is to visit the community with 3 enumerators from Monday, 16th March 2015.

Your assistance will be appreciated greatly.

Kind regards.

Maxon Lexon Chitawo

A3.6: Participants' consent form

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Malawi energy situation analysis: investigating the potential of bioenergy production from locally available primary forest plantations and agricultural residues.

You are asked to participate in a research study conducted by Maxon Lexon Chitawo, studying for PhD in Process Engineering Department at Stellenbosch University. The results of this study will contribute to research papers and a thesis for the aforementioned degree. You were selected as a possible participant in this study because of your profession/position and strategic role of your institution/sector in bioenergy development in Malawi.

1. PURPOSE OF THE STUDY

The purpose of this study is to assess the potential of bioenergy production from locally available primary forest plantations and agricultural residues (rice straws and husks) that are locally available in Malawi. The data will be used in development of a model and a framework for sustainable production of bioenergy in small scale decentralized systems for energy supply to rural communities.

2. PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

The researcher will request for a formal appointment to meet with you for the interview/discussion. You will be asked questions pertaining to your sector and or your involvement in energy, bioenergy production and policy issues relating to your sector in Malawi. The questions will be based on the discussion points provided on the sheet attached to this form. The discussion points are categorized according to the sectors in which energy and bioenergy production processes are interrelated. You will only be asked questions based on the discussion points pertaining to your sector and or profession. Where your response will refer to reports, the researcher may ask for a copy or will request for your permission to make a copy of the report for his reference. Your responses will be recorded both in print and in electronic formats. It is expected that the interview/discussion will take a maximum of 30 minutes.

3. POTENTIAL RISKS AND DISCOMFORTS

There are not anticipated risks in this survey.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

The research is solely for gathering information for an academic research on bioenergy development in Malawi and its practical implementation may not be in the immediate future.

5. PAYMENT FOR PARTICIPATION

Participation in this survey is voluntary

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of storing the information in lockable drive with pass word known only by the researcher and supervisor.

The information will be used for academic purposes in the thesis of the researcher for the award of PhD and in journal papers which will be published in peer reviewed journals.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so. You will however, be informed of any such circumstances that may arise.

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact Maxon Lexon Chitawo, Process Engineering Department, Faculty of Engineering, Stellenbosch University, Private Bag X1, Matieland, Stellenbosch. Cell:+27619712718. Dr. A.F.A. Chimphango, Process Engineering Department, Faculty of Engineering, Stellenbosch University, Private Bag X1, Matieland, Stellenbosch. Tel.: +27 619712718/+265 882 458 130. *Tel: +27 21 808 4094, Fax: +27 21 808 2059, Cell: +27 72 288 7538*

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; +27 (21) 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH PARTICIPANT

The information above was described to *me* by ____ in Chichewa/*English* and *I am the participant* in command of this language or it was satisfactorily translated to *me*. *I* was given the opportunity to ask questions and these questions were answered to *my* satisfaction.

I hereby consent voluntarily to participate in this study. I have been given a copy of this form.

____ _______________

Name of Participant **Date**

SIGNATURE OF RESEARCHER

I declare that I explained the information given in this document to ___________________ [*name of the participant]*. [*H*e/she] was encouraged and given ample time to ask me any questions. This conversation was conducted in *Chichewa/English*.

____ _______________

Signature of Researcher Date

Appendix A4: Questionnaires

A4.1: Viphya forest plantations management questionnaire

Systems approach in developing a model for sustainable production of bioenergy

Preamble

My name is Maxon L. Chitawo and I am conducting a survey to collect part of the data for my PhD research on *Systems approach in developing a model for sustainable production of bioenergy in Malawi*. The research is multidiscipline in nature combining technical and social aspects of sustainable bioenergy systems. It is focussing on bioenergy production in small scale decentralised bioenergy systems located in rural communities for supplying energy to rural households. The model to be developed will be used by policy makers and bioenergy systems developers for policy development and review and for the development of small scale bioenergy systems respectively.

You have been identified as one of the key stakeholders to participate in the survey by virtue of your profession/position and strategic role of your institution/sector in bioenergy development and biomass production in Malawi. Participation in the survey is voluntary and you are free to accept or reject to participate or to respond to any of the questions you deem to be uncomfortable with. You can also withdraw completely from participating in the survey even after responding to some of the questions if you feel your rights are being violated in the process of the interview/discussion.

The survey covers the following key topics:

(a) Harvesting and replanting of the Viphya Forest Plantation.

(b) Regulations/by-laws on use of the forest residues.

(c) Integration of energy production from the residues.

The survey will take about 20 minutes.

Viphya Plantation Forest Office discussion guiding questions

1. How many hectares of the Viphya Forest Plantation are harvested per year?
2. What is the estimated wood or wood related products yield in kg or m^3 per hectare?
3. What is the proportion of primary residues produced per year from the harvested wood from the forest plantations?
4. How are the forest residues disposed?

5. Has energy generation from forest residues in the plantation been considered as part of the Viphya Forest Plantation management plan?
6. What would be the opportunities of integrating energy generation from the residues in the management of Viphya Forest Plantation?
7. What would be the challenges of integrating energy generation from the residues in the management of Viphya Forest Plantation?
8. How much of the harvested forest plantation area is replanted per year?
9. When you compare trees planted per year and trees that actually grow, what is the survivor rate of the trees planted per year?
10. After planting the trees, how many years do you have to wait before the trees can be harvested (average maturity rate of trees in the plantations)?
11. How are local communities around the forest benefiting from the Viphya Forest Plantations?

A4.2: Rural households' energy survey questionnaire (used with permission from C. Zalengera, Energy Department, Mzuzu University, www.mzuni.ac.mw)

Objective: Understanding the energy needs and energy demand of rural communities that can influence choice of forms of energy, energy technologies and the impact this can have on sustainability of bioenergy technologies.

A. Energy needs and energy sources

1. Please tick the cells indicating how the following services are important to your community? 1= most important, and so on up to 5 = most unimportant.

	1	2	3	4	5
Portable water supply system for drinking and household use					
Water supply for irrigation					
Health service					
Electricity Supply					
Education services					

2. Which energy source do you use in the following activities? For each use please tick the cell below a relevant energy source.

	Firewood	Charcoal	Paraffin	Candle	Petrol	Diesel	Batteries	Gas	Electricity	Other
Cooking										
Lighting										
Water heating										
Radio										
Television										
Transport										
Farming and Livestock										
Industrial activities										
Drinking- water pumping										
Irrigation- water pumping										
Handcraft										
Telecommunication										
Other activities										

3. If electricity was supplied in this area what would you use it for? Mark numbers 1to 5 in the boxes you feel are key priorities for you with number 1 being the most important priority.

☐ Lighting ☐ Cooking ☐ Heating ☐Radio ☐TV ☐ Health Service Equipment
☐Education Services ☐Water supply ☐Telecommunication ☐ Irrigation (Farming) ☐ Other ______________

4. Indicate by ticking in the box(es) below to indicate the electrical appliances you have in your home.

☐ Radio ☐ TV ☐ Refrigerator
☐ Other (specify)
1. ____________________ 2. ________________ 3. ____________________ 4. ____________________

5. What other electrical appliances would you buy if youwould have access to electricity?

Appliance	When do you expect to have the appliances?
______________________________ ______________________________ ______________________________	____________________________ ____________________________ ____________________________

6. How much of the energy sources do you use **per month** on the activities indicated on the left column?

	Firewood	Charcoal	Paraffin	Candle	Petrol	Diesel	Batteries	Gas	Other
Cooking									
Lighting									
Water heating									
Radio									
Television									
Transport									
Farming and Livestock									
Industrial activities									
Drinking- water pumping									
Irrigation- water pumping									
Handcraft									
Telecommunication									
Other activities									

7. Please write down how much you spend **per month** on the following energy sources.

Firewood	Charcoal	Paraffin	Candles	Petrol	Diesel	Batteries	Gas	Electricity (if any)	Other (specify)

8. Which of the following activities that require energy indicated on the left column is most important to you? 1= most important; level of importance can be repeated. **Please tick the cell of importance against each activity.**

	1	2	3	4	5	6	7	8	9	10
Cooking										
Lighting										
Water heating										
Radio										
Television										
Transport										
Farming and Livestock										
Industrial activities										
Drinking- water pumping										
Irrigation- water pumping										
Handcraft										
Telecommunication										
Other activities										

9. If you use firewood, please indicate how you source the firewood.
   ☐ Collect for free from a local woodlot ☐ Buy from private sellers

   ☐ Collect from local woodlot and also buy from private sellers ☐ N/A

10. If you collect firewood, how many days a week do you go out to collect firewood?
   ☐ 1 day ☐ 2 days ☐ 3 days ☐ 4 days ☐ 5 days ☐ 6 days ☐ 7 days
   ☐ N/A
   Please state the **hours** you spend (including travelling time) collecting firewood each day you go out

____

11. Explain what you do **not** like about your current energy technologies/sources?

	What is not likeable
Firewood	
Charcoal	
Paraffin	
Candles	
Batteries	
Gas	
Petrol	
Diesel	

ESCOM electricity	

12. Explain what you like about your current energy technologies/sources.

	What is likeable
Firewood	
Charcoal	
Paraffin	
Candles	
Batteries	
Gas	
Petrol	
Diesel	
ESCOM electricity	

13. Would you still use your current energy sources (e.g. firewood for cooking) if you had other energy sources e.g. electricity ☐ Yes ☐ No
14. What can make you not abandon your current energy technologies/sources?

	Why energy source/technology cannot be abandoned
Firewood	
Charcoal	
Paraffin	
Candles	
Batteries	
Gas	
Petrol	
Diesel	
ESCOM electricity	

15. How satisfied are you with the energy sources you use for the following activities.

	Very dissatisfied	Dissatisfied	Satisfied	Very satisfied
Cooking				
Lighting				
Water heating				
Radio				

Television				
Transport				
Farming and Livestock				
Industrial activities				
Drinking- water pumping				
Handcraft				
Telecommunication				
Other activities				

16. State the quantity of hot water required per day for your household or institution

____

B. SOCIO-ECONOMICS

17. Please indicate the crops you grow and their respective annual production.

Crop type **Annual production** **Comments on uses and market outlets**

☐Maize _____________

____

☐Cassava _____________

____

☐Rice _____________

____

☐Other (specify) _____________

____

☐ N/A

18. Please tick the animals you tame. **Please write numbers in the spaces provided.**

☐ Goat _____ ☐ Ducks _______ ☐ Pigs ________ ☐ Cattle_____ ☐ Pigeon_____

☐ Sheep______ ☐ Chicken_____ ☐ Dogs________ ☐ Other (specify) ______☐ N/A

Comments on uses and market outlets:

____

____

19. Please indicate which of the following services you have access to.

☐ Microfinance Institutions ☐ Banks ☐ Cooperatives ☐Others (specify)

20. Have you received any loan in the past 12 months

☐ Yes No Reason:

____

21. Please indicate if you have access to loans for energy supply.

☐ Yes ☐ No

22. Please state profitable business enterprises in your area.

____

23. What form(s) of energy would the profitable business need?

____

24. Write down the business enterprise you do or you would want to engage in.

Current business enterprise____________________ Desired business enterprise ____________________

25. State any technical skills in your household or institution.

☐Carpentry ☐Tinsmith ☐Motor vehicle mechanics ☐Electrician ☐ Mechanic

☐Other (specify) ____

26. How satisfied are you with your income to cover for your food requirements
☐ Very dissatisfied ☐ Dissatisfied ☐ Satisfied ☐ Very satisfied
☐ N/A

27. How satisfied are you and your family with the following services in your area.

	Very dissatisfied	Dissatisfied	Satisfied	Very satisfied
Education services				
Health services				
Water supply for drinking				
Water supply for irrigation				
Electricity supply (if any)				

28. Please indicate if you have ever felt under financial pressure to source energy resources or pay for your energy bills / costs.
☐ Yes ☐No ☐ N/A

29. State how much you would be comfortable to spend on energy bills **per month** (cooking, heating, lighting, TV, radio etc. except transport). K ______________________________

30. State how much you would be comfortable to spend **at once** at a maximum towards purchasing an energy system (e.g. modern biomass energy system, solar PV system, diesel generator etc.).
K___________________

31. Please indicate if you own a piece of farmland.
☐ Yes ☐ No ☐ N/A Comment on ownership_____________

32. Please indicate the ownership of your property.
☐Private ☐ Family ☐ Rented ☐Government

33. Please indicate if you consider emigrating from this community.
☐ Yes ☐ No ☐ N/A Give a reason
____

34. Please indicate your employment status.
☐ Fulltime paid employment ☐ Farmer ☐ Business person /institution ☐ Casual labourer

35. Please state your **annual income** from the following activities.

	Amount
Animal-farming income	
Crop-farming income	
Employment/piece works income	
Business-enterprise income	
Aid	
Others	

C. WATER SOURCES

36. Where do you get water for your daily activities from?
☐River ☐Public borehole ☐Private borehole ☐ Others ________________

37. How much water do you use per day for household chores? ________________

Comment on proportions for major uses.____

38. How much water do you use per day for irrigation? _________________

39. Is the source of water for irrigation reliable to supply for the whole year____

D. COMMUNITY PARTICIPATION

40. Are there people in the community who participate in meetings about energy?

☐ Yes ☐ No

41. Do women participate in decision making in the community?

☐ Yes ☐ No

42. What is your opinion about security in the community?

☐ Good ☐ Acceptable ☐ Bad

Thank you for taking part in the survey.

A4.3: Stakeholders analysis questionnaire

Systems approach in developing a model for sustainable production of bioenergy in Malawi

Preamble

My name is Maxon L. Chitawo and I am conducting a survey to collect part of the data for my PhD research on *Systems approach in developing a model for sustainable production of bioenergy in Malawi*. The research is multidiscipline in nature combining technical and social aspects of sustainable bioenergy systems. It is focussing on bioenergy production in small scale decentralised bioenergy systems located in rural communities for supplying energy to rural households. The model to be developed will be used by policy makers and bioenergy systems developers for policy development and review and for the development of small bioenergy systems respectively.

Bioenergy

Bioenergy is renewable energy produced from organic materials such as plants (including trees and agricultural crops) and waste materials such as forest residues from timber production and processing, wood waste from mills, animal manure, municipal wastes, landfills, sewage sludge and wastewater treatment facilities. Most of these materials are locally available in Malawi but are unaccounted for and are underutilised. Processes and mechanisms that convert these organic materials into useful energy or energy sources are called bioenergy technologies. The choice of bioenergy technologies to convert biomass to useful energy or bioenergy products depends on the kind of biomass feedstock and the type of energy or energy products most needed by the end users. This study is aimed at developing a sustainable process of producing energy from primary forest residues and rice straws and husks. Primary forest residues and rice straws and husks are available in Malawi from Viphya and other government and privately owned forest plantations and from rice schemes respectively.

While biomass in the form of firewood and charcoal is the predominant source of energy accounting for 89% of the primary energy used in Malawi, its production and utilisation is unsustainable requiring innovative approaches to its processes along the value chain.

You have been identified as one of the key stakeholders in production of energy from primary forest residues and rice straws and husks by virtue of your profession, position and important role of your sector or institution, to participate in the survey in Malawi. Participation in the survey is voluntary and you are free to accept or reject to participate or to respond to any of the questions you deem to be uncomfortable with. You can also withdraw completely from participating in the survey even after responding to some of the questions if you feel your rights are being violated in the process of the interview/discussion.

The survey covers the following key topics:

(d) Category of stakeholder and potential role in bioenergy development in Malawi;

(e) Socio-economic aspects of bioenergy value chain;

(f) Bioenergy technologies transfer; and

(g) Community participation.

The survey will take about 30 minutes.

Objective: Understanding the stakeholders' roles/involvement and influence in bioenergy production from primary forest residues and rice straws and husks, bioenergy technologies transfer and the impact this can have on sustainability of bioenergy production in Malawi.

E. Category of stakeholder and potential role in generating energy from primary forest residues and straws

43. Please tick in the box that best describes your current position or profession or nature of your institution and activities you are currently doing.

Sawyer	

Farmer	
Policy maker - Energy	
Policy maker – Forestry	
Policy maker – Agriculture	
Regulator of the energy sector	
Transporter of residues to bioenergy production plant	
Member of a rural community and potential end user of the bioenergy	
Member of a rural community and potential employee for collecting, loading and unloading the residues	
Farmers Union	
Rice Scheme Management	
Labour union	
Environmentalist	
Gender activist	
Academic institution	
Viphya Forest Plantations Management	
Investor in bioenergy	
Energy supply company	
Community Based Organisation (CBO)	
Community Leader	
Local Government Authority	
Agricultural Development Division	
Trader (Business person)	
Others (specify)	

44. Tick in the cell below that provides relevant description of activities you would be doing in the processes of production of energy from forest residues and or rice straws and husks.

Producing residues from timber production activities	
Producing rice residues from rice farming activities and processes	
Invest in setting up a system for production of energy from the residues	
Supplying energy and other energy co-products to rural community	
Collecting residues from the harvested fields	
Loading and offloading residues on and from trucks respectively	
Transporting residues to places where systems for producing energy from residues will be located	

Policy formulation in energy	
Policy formulation in forestry and use of forestry residues	
Policy formulation in agriculture and use of agricultural residues	
Policy formulation at Local Government and local authority level	
Developing regulations the energy industry	
Promoting and implementing agricultural development programmes within a designated area	
Handling labour related issues of workers in the systems of energy production from residues	
Beneficiary of energy and co-products when generated from the residues	
Providing environmental audit and advice in the processes of producing energy from forest residues and rice straws and husks	
Rice milling	
Trading (selling) forestry wood products e.g. timber and forest residues (barks and or firewood)	
Trading (selling) rice and rice residues (straws and husks)	
Advancing interests, plight and welfare of framers	
Promoting livelihood of rural communities in a designated area	
Co-ordinating development programmes, settling disputes and managing administrative issues of a community	
Other activities (specify)	

45. Tick in the box that best describes your level of interest in production of energy from primary forest residues from Viphya Forest Plantations or from rice straws and husks when developed? Scale: Very High = 5, High = 4, medium = 3, low = 2, very low = 1 and Not interested =0
☐ Very High; ☐ High; ☐ Medium; ☐ Low; ☐ Very low; ☐ Not interested

46. Tick in the box that describes how your level of involvement would be in the process of producing energy from primary forest residues from Viphya Forest Plantations or from rice straws and husks if developed? Scale: Directly involved 6-7 days a week = 5, Directly involved 4-5 days a week = 4, Directly involved 2-3 days a week = 3, Directly involved 1 day a week = 2, Indirectly involved = 1, Not interested = 0
☐ Directly involved 6-7 days a week, ☐ directly involved 4-5 days a week; ☐ directly involved 2-3 days a week, ☐ directly involved 1 day a week, ☐ indirectly involved; ☐ not involved

47. Tick in the boxes that describe what would motivate you to be involved in the processes of producing energy from primary forest residues from Viphya Forest Plantations or from rice straws and husks if developed?
☐ Diversifying energy used in the community, ☐ source of energy for my household, ☐ source of energy for my business; ☐ opportunity for employment in the local community; ☐ business opportunity as transporter of the residues; ☐ source of energy for irrigation, ☐ source of energy for preserving agricultural produce, ☐ opportunity to reduce risk of forest fires, ☐ opportunity to reduce cost of clearing the forest plantation land for replanting, ☐ prospects to integrate bioenergy in forest management plans of forest plantations, ☐ source of energy for preserving agricultural produce, business, ☐ maximise

productivity of forest plantations through a zero waste framework to use residues for production of bioenergy,

48. What do you think would make you not to be involved or playing any role in the processes of producing energy from primary forest residues from Viphya Forest Plantation or from rice straws and husks?

F. Bioenergy technologies transfer

49. Tick in the boxes that describe technologies for producing energy from primary forest residues or from rice straws and husks that you are aware of.
☐ Combustion technologies for generating heat only e.g. cook stoves for cooking and water heating, rocket tobacco barns
☐ Combustion technologies for generating heat and electricity ☐ Gasification technologies for generating electricity,
☐ Pyrolysis technologies for producing charcoal, bio oils, bio char, ☐ Biomass to ethanol production technologies
☐ Biomass to diesel production technologies, ☐Biomass briquette making technologies,
☐ Biomass pellet making technologies, ☐Biomass torrefaction technologies, ☐ Biomass carbonisation technologies, ☐ Others (specify) ______________________________

50. Tick in the boxes that describe technologies for producing energy from primary forest residues or from rice straws and husks that are available in Malawi?
☐ Combustion technologies for generating heat only e.g. cook stoves for cooking and water heating, rocket tobacco barns
☐ Combustion technologies for generating heat and or electricity
☐ Gasification technologies for generating electricity, ☐ Pyrolysis technologies for producing charcoal, bio oils, bio char, ☐ Biomass to ethanol production technologies ☐ Biomass to diesel production technologies,
☐Biomass briquette making technologies, ☐ Biomass pellet making technologies, ☐Biomass torrefaction technologies, ☐Biomass carbonisation technologies,
☐ Others (specify) ______________________________

51. Tick in the boxes that describe technologies for producing energy from primary forest residues or from rice straws and husks that are commonly used in Malawi?
☐ Combustion technologies for generating heat only, ☐ Combustion technologies for generating heat and or electricity
☐ Gasification technologies for generating electricity, ☐ Pyrolysis technologies for producing charcoal, bio oils and bio char, ☐ Biomass to ethanol production technologies, ☐ Biomass to diesel production technologies, ☐Biomass briquette making technologies, ☐ Biomass pellet making technologies, ☐Biomass torrefaction technologies, ☐ Biomass carbonisation technologies, ☐ Others (specify) ______________________________

52. Tick in the boxes that describe technologies for producing energy from primary forest residues or from rice straws and husks that you are currently using.
☐ Combustion technologies for generating heat only, ☐ Combustion technologies for generating heat and or electricity
☐ Gasification technologies for generating heat and or electricity, ☐ Pyrolysis technologies for producing charcoal, bio oils, bio char, ☐ Biomass to ethanol production technologies, ☐ Biomass esterification for biodiesel production technologies, ☐Biomass briquette making technologies, ☐ Biomass pellet making technologies, ☐Biomass torrefaction technologies, ☐Biomass carbonisation technologies, ☐ Others (specify) ______________________________

53. Tick in the boxes that describe technologies for producing energy from primary forest residues or from rice straws and husks that can be sourced locally in Malawi.

☐ Combustion technologies for generating heat only, ☐ Combustion technologies for generating heat and or electricity
☐ Gasification technologies for generating heat and or electricity, ☐Pyrolysis technologies for producing charcoal, bio oils, bio char, ☐ Biomass to ethanol production technologies, ☐Biomass to diesel production technologies, ☐Biomass briquette making technologies, ☐ Biomass pellet making technologies, ☐Biomass torrefaction technologies, ☐ Biomass carbonisation technologies, ☐ Others (specify) ____

54. Tick in the boxes that describe renewable energy technologies support mechanisms that are available in Malawi which can be accessed to support technologies for production of energy from primary forest residues or from rice straws and husk.
☐ Duty waiver on imported technologies for producing energy from forest residues or from rice straws and husks, ☐ Fee-In-Tariffs Laws, ☐ Power Purchase Agreement, ☐ Tax holiday for a specific number of years for specific capacities of energy production systems, ☐ None, ☐ Not aware, ☐others (specify) ____

55. Tick in the boxes that describe the challenges to dissemination or increasing uptake of bioenergy technologies in Malawi.
☐ Unavailability of technologies for production of energy from primary forest residues or from rice straws and husk in Malawi,
☐ Lack of awareness of technologies for production of energy from primary forest residues or from rice straws and husk,
☐ Lack of capacity building programmes to develop technical expertise in technologies for production of energy from primary forest residues or from rice straws and husk,
☐ Lack of fiscal support mechanisms to development of technologies for production of energy from primary forest residues or from rice straws and husk in Malawi;
☐ Technologies for production of energy from primary forest residues or from rice straws and husk are expensive in Malawi, ☐ Lack of local entrepreneurs to manufacture technologies and spare parts for production of energy from primary forest residues or from rice straws and husk ☐ Others (specify)
____

G. Community participation in decision making and in economic activities

56. Has the community been involved in energy projects before?
☐ Yes ☐ No
57. Have the communities around the Viphya plantations benefitted from the plantations as source of energy?
☐ Yes ☐ No
58. Have the communities around rice schemes benefitted from the rice residues as a source of energy?
☐ Yes ☐ No
59. Do the communities participate in decision making in managing the forest plantations or rice schemes?
☐ Yes ☐ No
60. Do the communities participate in management and disposal of forest or rice residues?
☐ Yes ☐ No
61. Have the communities managed community development projects before?
☐ Yes ☐ No
62. Do women participate in decision making in the community?
☐ Yes ☐ No
63. What is your opinion about participation of households in development projects in the community?
☐ Good ☐ Acceptable ☐ Bad
64. What is your opinion about participation and households' willingness to pay for energy services in the community?
☐ Good ☐ Acceptable ☐ Bad
65. What is your opinion about security in the community?
☐ Good ☐ Acceptable ☐ Bad

66. Please tick the approximate proportion of men to women working in the Viphya Forest Plantation.
☐ 90:10, ☐ 80:20, ☐ 70:30, ☐ 60:40, ☐ 50:50, ☐ 40:60, ☐ 30:70, ☐ 20:80, ☐ 10:90
67. Please tick the approximate proportion of men to women owning rice farms or participating in rice farming as owners or heads.
☐ 90:10, ☐ 80:20, ☐ 70:30, ☐ 60:40, ☐ 50:50, ☐ 40:60, ☐ 30:70, ☐ 20:80, ☐ 10:90
68. Please tick the approximate proportion of men to women owning businesses as owners or heads.
☐ 90:10, ☐ 80:20, ☐ 70:30, ☐ 60:40, ☐ 50:50, ☐ 40:60, ☐ 30:70, ☐ 20:80, ☐ 10:90

End of survey questions

Thank you for taking part in this survey.

Appendix A5: Table for determination of sample size (Bartlett et al., 2001)

Table 1: Table for Determining Minimum Returned Sample Size for a Given Population Size for Continuous and Categorical Data

	Sample size					
	Continuous data (margin of error=.03)			Categorical data (margin of error=.05)		
Population size	alpha=.10 t=1.65	alpha=.05 t=1.96	alpha=.01 t=2.58	p=.50 t=1.65	p=.50 t=1.96	p=.50 t=2.58
100	46	55	68	74	80	87
200	59	75	102	116	132	154
300	65	85	123	143	169	207
400	69	92	137	162	196	250
500	72	96	147	176	218	286
600	73	100	155	187	235	316
700	75	102	161	196	249	341
800	76	104	166	203	260	363
900	76	105	170	209	270	382
1,000	77	106	173	213	278	399
1,500	79	110	183	230	306	461
2,000	83	112	189	239	323	499
4,000	83	119	198	254	351	570
6,000	83	119	209	259	362	598
8,000	83	119	209	262	367	613
10,000	83	119	209	264	370	623

NOTE: The margins of error used in the table were .03 for continuous data and .05 for categorical data. Researchers may use this table if the margin of error shown is appropriate for their study; however, the appropriate sample size must be calculated if these error rates are not appropriate. Table developed by Bartlett, Kotrlik, & Higgins.