Using Multi Criteria Decision Analysis To Develop Sustainability Assessment Tools: Biomass Supply Chains

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USING MULTI CRITERIA DECISION ANALYSIS TO DEVELOP SUSTAINABILITY ASSESSMENT TOOLS: BIOMASS SUPPLY CHAINS

A Thesis Presented

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Deandra Perruccio

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Abstract

Energy access remains a significant challenge in nations lacking access to resources and strong infrastructure systems, creating barriers to economic development and to increased standards of living. Small scale biomass gasification energy (BGE) systems have been developed to meet energy needs in rural areas, creating synergies between agricultural and agro-forestry systems through utilization of biomass feedstock for energy generation. The sustainability of such systems requires sophisticated planning and coordination of the biomass supply chain.

The goal of this thesis is to investigate and improve structural and process related characteristics of sustainability assessments for small scale bio-energy systems, specifically focusing on establishment and management of biomass supply chains through the development and dissemination of a generic sustainability assessment framework for biomass supply chains of small-scale BGE systems in rural East Africa. Building on a preliminary sustainability assessment framework (Christensen, 2013; Joerg, 2013) this research develops an assessment tool designed to capture sustainability requirements of the biomass supply chain in the ecological, social, and economic spheres through testing on three case studies in rural Uganda. Application and analysis of a preliminary framework on pilot projects in a rural east African context using Multi Criteria Decision Analysis (MCDA) methodologies contributes to development of strategies for energy system analysis and building stakeholder capacity to incorporate social, economic, and environmental considerations. The assessment process is outlined, including scoring, data collection, contextual considerations. Model application is discussed, including the impact of weighting on decision outcomes, uncertainty management, sensitivity analysis, and identification of tradeoffs among criteria. Finally, discussion of tool usefulness verses usability contributes to bridging academic research with practitioner priorities.
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Chapter 1  
Introduction

As recognition of human impact on ecosystems grows, public institutions and private sector businesses are looking for ways to define and formalize the changing perspective in planning and resource management. Sustainability assessments are being developed to incorporate social, environmental, and economic considerations into decision-making at a strategic level, facilitating deep conversation, meaningful learning, and formulation of explicit, transparent definitions of sustainability goals. Developing decision tools which incorporate an evolving understanding of corporate or organizational goals is necessary to integrate sustainability principals into operations.

This research will contribute to the literature informing application of sustainability principals at the project level by building groundwork for a larger research effort in building, implementing, and disseminating a generic sustainability assessment framework for small-scale bioelectricity systems in rural East Africa.

The incorporation of, and symbiotic relationship between energy generation, natural resources, and human stewardship is an important element which sets bio-energy systems apart from other renewable energy options. Bio-energy systems have a unique opportunity to create additional economic activity and environmental benefits in a community not only through the generation of electricity and valuable byproducts, but also through the establishment of the biomass supply chain.

Such systems are highly complex, involving sophisticated management structures for feedstock supply production and processing, technical system operations, energy deployment, and customer/business management (Buchholz et al., 2009). In addition, a system with sustainable management goals may incorporate added social and environmental considerations in decision-making, as well as engage a larger number of stakeholders (Buchholz et al., 2009).

Dissemination of renewable technology systems often fail not in the technological application itself, but rather in lack of understanding of the complexity inherent in the wider receiving environment, and a resulting lack of preparation and support for the management of this broader system (Anadon et al., 2014; Jenkins, personal communication 2014, Buchholz, personal communication, 2014; Gosh et al., 2003). Robust decision-making in this large and intricate system requires support for problem structuring and processing.

Scaling resource demands to the local ecosystem’s carrying capacity, efficient resource use, and fair distribution are therefore essential considerations to unleash the
advantage of small-scale bioenergy production (Buchholz and Volk, 2012). The resulting complexity is difficult to manage at this scale and is beyond the capacity of small companies implementing bio-energy systems, resulting frequently in project failure (Buchholz et al. 2009).

There is a need for an assessment and monitoring tool that i) synthesizes relevant information from all components of such a small-scale bioenergy system ii) integrates the social, economic and environmental context iii) facilitates communication amongst stakeholders in a time and cost efficient process (Buchholz et al. 2012) and (iv) enables elicitation of trade-offs among social, environmental and economic goals (Zia et al. 2011; Zia et al. 2015).

This thesis will present a sustainability assessment framework, process toolkit, and modeling tool for decision-making around biomass supply chains for small scale bio-energy systems. In the article use of the framework and MCDA tool is demonstrated through application on two case study sites and variables are further explored for importance through investigation of weighting impacts on criteria scoring. Sensitivity analysis is also conducted to identify influential indicators and criteria. The second section of the thesis provides the sustainability assessment framework, MCDA software model, and user guide as a toolkit for supply chain management.

The review of current literature in chapter two provides relevant background information and current research regarding sustainable development, sustainability planning, bio-energy systems, and case study context.
Chapter 2  Literature Review and Objective

2.1 Comprehensive Literature Review

The literature review will cover the following topics:

- Sustainability from theory to application
  - History of the concept of sustainability and defining “sustainable”
  - Sustainability Assessments
  - Multi-Criteria Decision Analysis (MCDA)
  - Criteria and Indicator Frameworks
- Biomass Gasification and Bio-energy systems
- Case study context

2.1.1. Sustainability from theory to application

2.1.1.1 Global movement toward sustainable development

The concept of sustainability and sustainable development has grown with recognition of human impacts on earth systems. Its implementation into current societal systems at all scales has been slow and challenging. The research conducted in this study investigates an attempt to bridge the divide between theoretical/conceptual understandings of sustainability and its application. This section reviews the development of the concept of sustainability.

The creation of the Bretton Woods Institutions following WWII provided space for discussion, and authority for action, regarding development at a global level. While global politics, international relations, and strategic alliances shape the scope and influence of actors like the World Bank, International Monetary Fund (IMF), United Nations (UN), and World Trade Organization WTO, these institutions currently operate as the dominant authorities in global level social and economic organization.

When established, the Bretton Woods institutions were tasked to “promote a policy of expansion of the world’s economy…By expansion we should mean the increase of resources and production in real terms, in physical quantity, accompanied by a corresponding increase in purchasing power” (Rich, 2000, taken from Daly & Farley, 2004). The goals set by these decision-makers reflected a culture and experience of an “empty world” with limitless natural resources, few and manageable effects of environmental degradation, and limited understanding of the impact increasing technological advancements would have on extraction, production, transportation, and
consumption demands. In the past six decades the population has tripled, and resource “throughput” (flow of raw materials from resource to waste) has increased nine-fold (Daly & Farley, 2004). As Daly and Farley (2004) point out; we are now living in a “full” world. Economic thinking and governing institutions need to recognize and adapt to that reality.

In 1984, The Brundtland report introduced “sustainable development” to the international community through a UN panel established to develop long term environmental strategies for governing the international community (Elliot, 2006). In 1992 the UN Conference on Environment and Development, called the Earth Summit, took place in Rio de Janeiro, Brazil. This was at the time the largest ever international conference, with over 170 governments in attendance, 2,500 NGO’s, and 8,000 accredited journalists (Adams, 2001; O’Riordan, 2000; from Elliot, 2006). Sustainability, especially within western nations, had reached an audience beyond the traditional environmental circles, and consensus was emerging that sustainable development was an important consideration needing research and policy support (Elliot, 2006).

In 2002, Johannesburg, South Africa, the World Summit on Sustainable Development (WSSD) was marked by evidence of the realization complexity involved in achieving sustainable development, new understandings related to power, conflict, and natural resources, and increased representation by developing world interests suggesting new ways of approaching sustainable development including a more decentralized understanding of where change comes from (Elliot, 2006; Bigg, 2004).

Most recently, in 2012, the Rio+20 Earth Summit concluded with commitments to work toward alternative indicators to GDP, increased support for the UN Environment Programme (UNEP), and development of Sustainable Development Goals (SDG’s) which pick up where Millennium Development Goals fall short (Agreement, 2012). However, note-able absences of important heads of state including the US and weak language in regard to action steps by participants prompted reactions of disappointment and outrage among many in the global community (Agreement, 2012; Watts & Ford, 2012). While disagreement and unwillingness to cooperate among nations during the conference resulted in anger and frustration from constituents, 17 goals are ready to formally replace the Millennium Development Goals in September and progress is moving slowly toward developing systems for achieving and evaluating progress (Lu et al., 2015).

Sustainability has become an important part of the conversation across scales from firms to international agreements, and the nature of the issue requires cooperation, agreement, and action at a global level. While the term has become well known, there remains much work to shift societal behavior to reflect a sustainable reality.
2.1.1.2 Defining sustainability

Within the Brundtland report sustainable development is widely defined as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’. Elliot’s first chapter in *An Introduction to Sustainable Development* (2006) gives an analysis of the key debates within the previously separate development and environmental fields which highlights continuing sources of conflict in defining the terms sustainability and sustainable development. An example is provided of discussion defining sustainable development during the Rio Conference, which produced the ‘Agenda 21’ document. Tension was evident between environmental concerns of rich and poor countries; those who wished to conserve resources, many of whom’s resource use for development lies in the past, and those who see a need to exploit resources to produce growth in their own economies (Elliot, 2006).

Daly and Farley break the idea of sustainable development down farther in their book *Ecological Economics*, creating distinct separation between growth, as measured by an increase in throughput, with development, defined as qualitative change or evolution toward an improved but not larger structure or system. They define sustainable development as development without growth- that is, “qualitative improvement in the ability to satisfy wants (needs and desires) without a quantitative increase in throughput beyond environmental carrying capacity” (Daly & Farley, 2006). Their discussion highlights the confusion of quantitative and qualitative indicators in determining the desirability of “development” as evidenced through focus on measures like GDP.

The term sustainability has become popular to the point of fad status, seemingly undermining its important meaning, yet bringing unprecedented attention to issues of environmental degradation, energy use, and consumption. If the popularity of the term reflects a growing consciousness and movement or shift in societal perceptions, it follows that there will be some lag as policies, companies, institutions, and individuals’ attempt to incorporate those changing values into operations and culture. In December of 2014 the EU passed legislation requiring large companies to conduct sustainability reporting including environmental and diversity information. The directive making sustainability assessment law is part of a larger effort by the EU to incorporate social responsibility and sustainable planning toward the five Europe 2020 goals around sustainable, inclusive development (Sustainability, 2015). Constant reflection and evaluation are necessary to avoid “green washing” and regression, and debate will undoubtedly continue around the meaning and implementation of sustainability and sustainable development. In light of the divergent understanding of what sustainability means and looks like, many experts hold stakeholder participation, transparency, and inclusion as the litmus test when determining the validity of goal setting around sustainability (Elliot, 2006; Gibson, 2006; Grace & Pope, 2006).
2.1.1.3 Sustainability Assessments

As recognition grows of the significant impact human activity is having on ecosystems, public institutions and private sector businesses are looking for ways to define and formalize this changing perspective. Environmental Impact Assessment (EIA) is the current accepted strategy for assessing environmental impacts in planning arenas. However many claim this method is both too narrow and lacks a strategic element, often coming into a project development at the final stages of the process (Amezaga et al. 2010; Gibson, 2006; Noble, 2000). Sustainability assessments are being developed to incorporate social, environmental, and economic considerations into decision-making at a strategic level, facilitating deep conversation, meaningful learning, and formulation of explicit, transparent definitions of sustainability goals.

2.1.1.3.1 SA in practice

Sustainability assessments are increasingly being used in both the private and public sector from project level to broad strategic planning. They are being used in certification schemes within the fields of sustainable forest management and agricultural practice (Buchholz, 2009), for project level and regional public environmental planning (Pope and Grace, 2006) and increasingly within the field of bioenergy for project development (Scott, 2012).

While the topic of this particular study is assessment of a focused and well defined question; how sustainable is a given biomass supply option in the context of small scale gasification system development in rural Uganda; Overall, sustainability assessments work best when partnered with and nested in a broad, strategic shift in policies at the institutional level (Grace and Pope, 2006). Although bottom-up approaches to integrating sustainability are attractive because they can move ahead more quickly, feedback mechanisms are needed to allow trickle-up learning that ensures policy gaps are exposed, recognized, and addressed, delivering benefits beyond individual projects.

Sustainability assessment encompasses a broad range of formal methodologies for evaluation of social, environmental, and economic impacts in management scenarios at a range of scales including the project, regional, or national level (Hacking and Guthrie, 2008; Amezaga et al., 2010). It provides a means for qualitative data to be integrated into the assessment process along with analytical data generated by scientific or technical studies (Pope and Grace, 2006). This opens the door for consideration of a wider body of knowledge regarding sustainability from bodies of understanding that lay beyond analytic, quantifiable measures. Sustainability assessments can also allow for recognition, discussion, and reconciliation of divergent interests across power scales, aiming to force explicit definition of objectives and encourage dialogue among stakeholders which may range from local to global actors.
It is recognized that capturing the whole collection of factors encompassing each of these spheres at all scales within one assessment is often neither feasible nor desirable. Hacking refers to the range of assessments offering varying degrees of comprehensiveness, integratedness, and strategicness (Figure 1) (Hacking and Guthrie, 2008).

![Figure 1. Features of sustainable development- directed features within the assessment process. (Hacking and Guthrie, 2008).](image)

While this variance in types, methodologies, and definitions within the sustainability assessment field strikes some as problematic, many argue this flexibility is an inherent characteristic of a tool meant to encompass a wide variety of contexts, goals, and decision problems. Rather than fault the broad assessment approach, there is a call to be explicit in setting clear goals, defining “success” in an inclusive way that engages stakeholders and designing a methodology that will address these goals (Hacking, 2008; Pope and Grace, 2006; Gibson, 2006). Indeed renowned systems theorist Donella Meadows points out that in any system, leverage points with the highest impact potential exist at the scale of goals and values (Meadows, 1999). The biggest and most powerful decisions are those made in the early stages outlining goals, objectives, and the scope of assessments (Gibson, 2006).
Sustainable use of biomass to address energy needs and sustainable development is a newly reinvigorated and emergent field. As it has developed there has been a natural progression of assessment and planning tools from similar industries including sustainable forestry and agriculture. Indicators for sustainability assessment in the forest management field have a longer history of application, supporting body of literature and convergence of measurements (McDonald & Lane, 2002; Meyer & Priess, 2014). Bioenergy assessment development has pulled methodologies, methods and relevant data from this body of literature.

2.1.1.3.2 A burgeoning field

While advancements in this relatively new approach differ across contexts, in many cases it has been a largely bottom up approach, with little formal methodological guidance or major institutional, legislative reform (Pope and Grace, 2006; Buchholz et al. 2009; Amezaga et al., 2010). In these cases sustainability assessments have an experiential and cyclical learning quality, where application is used to inform policy, which is then adapted to guide future application. This method of adaptive management promotes a cyclical relationship between theory and application and allows movement forward as a part of the development process through a “learn as we go” approach, a quality that will not only encourage adoption of sustainability thinking into social systems through trial and error application, but also result in a more robust, inclusive, and resilient set of tools and outcomes (Lawrence, 1997). Pope and Grace outline an example of synergistic development between assessment application and policy creation in Western Australia (Pope and Grace 2006). The rural planning process for developing countries is often a top down approach, with little opportunity for input at the local or regional level (Amezaga, 2010). This is an important consideration impacting assessment strategies for both public and private entities operating in emerging economies.

There is also concern in the environmental planning field that a shift from the narrowly defined environmental impact assessment towards project evaluations which weigh social and economic considerations provides an avenue for profit motivated proponents to subvert important environmental considerations or thresholds (Pope and Grace, 2006; Gibson, 2006). This concern highlights the importance of a transparent, inclusive process with authentic stakeholder input across local to international scales.

2.1.1.3.3 Considerations in application

While the idea of sustainability has gained attention in recent years, understanding and implementation of its principals are difficult to move from theory to application. Addressing environmental and social concerns prove much more difficult to implement than they are to talk about and as Hacking (2008) points out, “A great deal
of work may still be required to develop assessment techniques that deliver practical results capable of supporting the lavish policy-level commitments to Sustainable Development”.

2.1.1.3.3.1 Understanding and incorporating context

It is important to understand the context within which assessments are being proposed and implemented. The cultural traditions and norms, existence and operation of physical and political infrastructure as well as economic conditions will impact the development of successful sustainability assessments (Pope and Grace, 2006; Mardsen, 1998). As Pope and Grace point out, it is important when discussing application methods through experience to clearly describe these contextual details. Prescribing method without considering and learning from context can cause assessments to lose the sophistication and flexibility in assessment structuring that is needed to achieve robust learning, and result in less than desirable outcomes.

2.1.1.3.3.2 Participatory and transparent

There is a need to meaningfully engage the broader community, create space for deliberation, consideration of both qualitative and technical data, and identification of alternatives. Assessments work well when they are a participatory stakeholder process which forces deep thinking about the issue, and allows serious reflection on definition of goals and ensuing measures. As will be seen in this study, time and resource pressures can act as barriers to, and finding a productive balance between efficiency and valuable learning through an intensive process is an important consideration.

2.1.1.3.3.3 Struggles to avoid reductionist tendencies of the three pillar approach

Sustainability encompasses complex and interrelated systems, such that the overall system and its interactions become something greater than the sum of its parts. It necessitates and is encouraging a movement from the standard market-government model towards multi-party governance. Concerns of stakeholders and citizens often do not fit neatly but, combine economic, social, and environmental concerns, and therefore assessment structures should avoid overemphasis on the three-pillar model whose framing often results in perspectives of competing choices necessitating trade-offs rather than allowing discovery of synergies and mutual benefits across “pillars”(Gibson, 2006). There is a call for effort to embrace an approach that represents the integrated nature of sustainability assessments, develop aggressively integrative package of structure and process design features (Gibson, 2006). The integration may however lead to trade-offs among goals, and generate unintended
consequences and losers and winners in specific assessment contexts (Hirsch et al. 2011, Zia 2013)

Developing structures that accurately represent these relationships while maintaining a level of simplicity which provides functionality, however, remains a challenge. Current institutional organization encourages silo-ing of knowledge and management practices, creating significant barriers to transdisciplinary approaches (Gibson, 2006). Perhaps as a result of these tendencies, much of the literature is cordoned into highly specialized discussions of specific methods in case by case analysis with little consensus at broader levels around the integration piece of the assessment process. Meyer and Price (2014) provide an example of attempts to address comprehensiveness in these highly specialized schemes, including use of the Ecosystem Services Cascade (ESS) to define linkages and impacts of system level functions and structures. Their complex analysis highlights the tension within the field between specialization and functionality. A challenge remains to find the “sweet spot” between accurate representation of system complexity and functional processes that work to aid us in defining and achieving goals of sustainability. Increased integration of complexity science with management and decision fields may offer sophisticated tools for integrating this complexity into the decision-making process without creating overly-complex representations which become more burdensome than helpful.

2.1.1.4 Criteria and Indicator Frameworks

Criteria and Indicator Frameworks gained prominence as a tool for managing for sustainability in the early 1990’s. The Brundtland report and UN Conference on Environment and Development 1992 report outlined broad principles for sustainable resource management which were taken, adapted and further developed for use in forest management (Christensen, 2012). As technological improvements, sustainability, and energy security concerns cause biomass energy systems to become more popular, Criteria and Indicator frameworks have become standard practice within the field, resulting in robust structures for management decisions at a range of system scales from international resource governance schemes to project level analysis.

In Criteria and Indicator frameworks, criteria refer to the aspect of sustainability considered in the management, for example biodiversity, natural resource management, and rights of the local community. Indicators refer to the measurable quantities or values which correspond to a certain criterion and can be assessed to monitor the changes and progress of a forest and community (FAO,2012). C & I frameworks work to address the needs within sustainability management to synthesize large amounts of data and information as well as integrating different knowledge
disciplines, and “to accommodate scientific comprehensiveness, accuracy and practical feasibility (costs of implementation and technical-administrative feasibility)” (Rametsteiner et al. 2011).

The C&I framework methodology has been used by a wide range of organizations, private corporations, public planning agencies, and certification boards. Well known examples are FSC and PEFC for sustainable forest management, the Roundtable on Sustainable Biofuels (RSB), projects funded by the European Commission, organic certification and fair trade schemes (Christensen 2012, Rametsteiner et al, 2011). Standards and criteria consulted when developing the sustainability assessment framework drafted for this research (Christenson 2012) include Roundtable on Sustainable Biofuels (RSB, 2010); Council on Sustainable Biomass Production (CSBP, 2012); Naturland Standards on Production (Naturland, 2011), East African Organic Products Standard (UGOCERT, 2007); Forest Stewardship Council (FSC, 1996), Program for the Endorsement of Forest Certification (PEFC, 2010), Fairtrade Standards for Timber and Forest Enterprises (FLO, 2011).

The proliferation of C & I as a tool for sustainability planning has also lead to a large body of literature and evidence regarding methodology, framework structuring, and analysis techniques. While indicators are largely reliant on, and emergent from the natural science bodies of knowledge, emphasis is also being placed on the process of framework development, including criteria and indicator definition in an effort to integrate objective scientific measures with normative social/political interests (Rametsteiner et al. 2011). Review of current multi-criteria decision-making methodology for bio-energy systems identifies a number of methods and wide range of applications within the field. MCDA and C & I applications within the bioenergy field include project planning and sustainability related decision making, investigating social, economic, environmental issues in conjunction with operational considerations like location, capacity, technology selection (Scott et al., 2012).

The variety of methods within C & I methodologies is reflective of the range of framework applications, and indicative of the importance of setting clear goals and inclusion of stakeholders to guide use of the decision tool. While some level of convergence regarding the methods for analysis and decision making will improve cross-wise comparisons, clarification of best practices, and, theoretically, on-the-ground outcomes, emphasis on the framework as a learning tool and the importance of the process are frequently highlighted as measures of successful planning in management scenarios covering a range of complex systems requiring highly contextualized decision strategies (Grace & Pope, 2006; Nelson, 2006).

2.1.1.5 Multi Criteria Decision Analysis (MCDA)
2.1.1.5.1 Introduction to MCDA

Multi Criteria Decision Analysis is “a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter” (Belton and Stewart, 2006). As decisions become more complex, including multiple factors, stakeholders, potential impacts, and alternatives, decision aid processes including those found within MCDA become important tools for reaching well-reasoned, transparent, and inclusive solutions.

MCDA offers a way to formalize the decision process, allowing explicit definition of goals, problem structuring to organize the decision process in a way that is inclusive and methodical, forces hard thinking about the issue, makes clear subjectivities, and overall improves the final decision outcome. In short it promotes good decision making (Belton and Stewart 2002; Keeney and Raiffa, 1972). It provides a language for communication among stakeholders, a structure for the decision process, and a transparent trail of breadcrumbs with which to justify decisions. (Zeleny, 1982; French, 1989; Belton and Stewart, 2002).

MCDA has developed within Management Science, drawing theory and application principals from various schools of thought within the field, as well as from a variety of disciplines and theories including economics, social choice science, computational and programming sciences, and complex systems in a problem based, integrated approach (Belton and Stewart, 2006; Koksalan et al., 2011). The resulting “jack-of-all methods” quality of MCDA reflects an intentionally inclusive and open mentality designed to afford practitioners the flexibility necessary to address a large number of divergent problems decision makers are faced with across the plethora of worlds touched by social organization and management.

MDCA encompasses a wide range of methodologies, and methods which are highly context specific. As previously discussed, a key strength lies in MCDA’s ability to adapt to a range of decision problems, contexts and desired outcomes. Stewart and Belton (2002) offer a useful description of the MCDA process, explaining it as an iterative process pulling from adaptive management design and aimed at maximizing flexibility to move around within the decision process structure within varying time constraints. They highlight a need within literature to integrate the commonly fragmented discipline which they claim has fractured into highly specialized publications addressing particular approaches.

Their approach then aims to share and integrate different MCDA methods within an application framework to better equip practitioners, who face a myriad of decision problems, to understand and select appropriate tools from these many options. They connect MCDA with methods across the broad field of management science as well as
to quantitative tools from areas including operational research, management systems, and statistics, identifying synergies with MCDA approaches to develop nimble, sophisticated, problem-based decision aids and well-versed, capable, flexible facilitators. The iterative MCDA process defined by Belton and Stewart includes three major phases;

1. Identifying and structuring the problem
2. Model building and using the model to inform and challenge thinking
3. Ultimate determination of action plan

While the literature often begins from a starting point of well defined problems and jumps directly into analysis from this juncture, in reality problem structuring is one of the most important parts of the decision process, defining the boundaries of the issue and strongly influencing all subsequent decision options (Belton and Stewart, 2006; Pope and Grace, 2006) The first stage of the MCDA process is ideally characterized by divergent thinking, opening up of the issue and beginning to understand the complexity of the issue and how it might be managed. The model building and use stage involves convergent thinking, extracting the essence of an issue from its complex representation to a form that supports more detailed and precise evaluation of potential ways forward.

An important characteristic of the MCDA process is its cyclical nature. New knowledge and understanding at different stages of the process may cause a cycling back to adapt or restructure previous definitions or structures (Belton and Stewart, 2006; Phillips, 1990).

2.1.1.5.2 Limitations and considerations

MCDA literature is careful to clearly define best practice in the use of MCDA, and dispel common myths regarding its capabilities and purpose. As Belton states “The aim of MCDA should be, and principal benefit is, to facilitate decision makers understanding of the problem faced, about their own, other parties’, and organizational priorities, values, and objectives, and through exploring these in the context of the problem to guide them in identifying a preferred course of action” (Belton and Stewart, 2002).

The value of MCDA lies within the process rather than any final decision action or prescriptive recommendation therefore emphasis must be intentionally directed at creating and facilitating a robust process (Zeleny, 1982). Here facilitator experience and skill becomes an important component of successful MCDA application (Belton and Stewart, 2002).
Critiques of MCDA claim it is a prescriptive approach, prohibiting the nuanced understanding required when considering complex problems. However, those in the field see this as a simplistic understanding of the methodology, describing a purpose and process that is itself more nuanced in its application and sophisticated in its logic. French, in response, describes decision analysis as a delicate and subtle tool that helps decision makers better understand their beliefs and preferences, provides a language and formalism for the decision process, and facilitates communication between stakeholders (French, 1989).

MCDA models have also been criticized as too simplistic. There is a misunderstanding within that assumption about the simple model which ignores the involved process leading to simplicity. In MCDA simple models useful to the decision process emerge from distilling key factors in a transparent way that generates better understanding. (Belton and Stewart, 2002). The complexity, rigor, and highly involved learning process inherent in this “science of synthesis” should not be understated by deceivingly simple models as their simplicity serves a purpose of refining the decision problem, informed by participatory learning during model generation itself.

2.1.1.5.3 MCDA In practice- use for bio-energy systems

Biomass gasification energy (BEGE) systems are complex, involving sophisticated management structures for feedstock supply production and processing, technical system operations, energy deployment, and customer/business management. (Buchholz et al., 2009) In addition, a system with sustainable management goals may incorporate added social and environmental considerations in decision-making, as well as engage a larger number of stakeholders in order.

Dissemination of renewable technology systems often fail not in the technological application itself, but rather in lack of understanding of the complexity inherent in the wider receiving environment, and a resulting lack of preparation and support for the management of this broader system (Jenkins, personal communication 2014, Buchholz, personal communication, 2014). Robust decision-making in this resultantly large and intricate system requires a level of understanding that is beyond an individual’s cognitive ability unassisted. MCDA offers support for problem structuring and decision-making in complex problems, resulting in better informed, intentional decision-making.

2.1.1.5.4 “Learn by doing” approach- adaptive management and iterative processes- refinement through application

While there has been much debate about the correct definition of sustainability, an abundance of literature working to get sustainability assessments right, and constant
iterations of MCDA methodologies to better map real scenarios, Grace and Pope offer sound advice when they call for a “learn by doing” approach to implementing sustainability planning (Grace & Pope, 2006). Perfection will never be obtained, and too much debate and argument over achieving the silver-bullet solution wastes unnecessary energy that could be put into more productive use. Trial and error, with intentional reflection, information sharing, and learning, can achieve significant and sweeping changes over relatively short time spans.

William Easterly argues in White Man’s Burden (2006) that “searchers”, those looking for piecemeal solutions to seemingly minute problems often create gradual, but more authentic, robust and lasting changes than any top-down “planner” strategies can achieve. Sustainability planning needs to be addressed at both ends of the spectrum, but a “learn by doing” approach which incentivizes innovation and action alongside debate and discussion is an important mentality for more rapid movement forward.

Easterly, in a discussion about pursuit of development strategies within the World Bank claims that program should always expect some level of failure at some point, otherwise interventions were most likely not drastic enough (Easterly, 2006). Innovation requires action, and learning occurs best through rich experience. Any sustainability planning agenda will ultimately be more effective by adopting a well designed “learn by doing approach”.

2.1.2. Research Context: UGANDA

2.1.2.1 History, Geography, Society, Economy

Uganda is a landlocked country in East Africa that is roughly the size of Colorado (236,000 sq km). It is called the Pearl of Africa for its wide variety of terrain; mountains, grasslands, lakes, and rivers. The population of Uganda is estimated to be around 35.92 million in 2014 (CIA World Fact Book, 2014), and about 15% of this is urban population. The population growth rate is estimated at 3.25% on average between 2010-2015, ranked 4th highest in the world for population growth rate in 2012 and 48% of their population is under the age of 14 (CIA World Factbook, 2014).

Western-led International “development” efforts beginning with the creation of the IMF and World Bank have resulted in over 1 trillion dollars of aid in the form of concessional loans or grants entering the continent of Africa over the last half-century (Easterly, 2006). The infusion of economic and political influence has not led to sustained, healthy, and independent economic systems (Moyo, 2009; Easterly, 2006; Stiglitz & Charlton, 2005). Uganda’s per capita gross national income in 2012 was $585.00. Life expectancy is about 54 years. (UN World Statistics Pocketbook, 2014). Uganda’s export to import ratio is -3686 million USD, about 17% of their GDP of 21,736 million USD in 2012. Their number one import for 2011-2013 was petroleum.
There are ten major tribes and a number of smaller tribes represented in the Ugandan nation from five major kingdoms. The tribal make-up of Uganda is: Baganda 16.9%, Banyankole 9.5%, Basoga 8.4%, Bakiga 6.9%, Iteso 6.4%, Langi 6.1%, Acholi 4.7%, Bagisu 4.6%, Lugbara 4.2%, Bunyoro 2.7%, other 29.6% (CIA World Factbook, 2014). Tribal identity carries significant weight in Ugandan culture, although intermarriage, urbanization has begun to blur lines and dull points of contention.

The national literacy rate is 73.2%, meaning over 25% of the population cannot read or write and the school life expectancy is 11 years (CIA World Factbook). In 1999 universal primary education was funded by the government. School enrollments increased from 3 million to 5.3 million in 1997, and was seven million by 2004, however poor supporting infrastructure continues to cause issues of quality in education (Ngaka, 2006).

Following their independence in 1962, a string of single party rulers with questionable rule of law and poor economic policies created periods of instability and conflict in the nation until Yoweri Musevini took control in 1982. Musevini pulled government leadership from across tribal lines, reinstated monarchies of traditional Ugandan kingdoms, developed more accountable rule of law and encouraged tourism (History, 2014).

In 2006 multi-party elections were restored, however the leading opponent was imprisoned prior to the election. To the growing consciousness and dissatisfaction of Ugandans corruption permeates all levels of society, most objectionably at the level of national politics. A deeply religious society, with a majority of practicing Christians and large minority of Muslim citizens, traditional values around honesty stand starkly against the behavior of leadership and culture of bribery normalized in government (Gureme, 2006). Conflicts in South Sudan, Democratic Republic of Congo, and within Northern Uganda from a terrorist group the Lords Resistance Army (LRA) has caused intermittent instability in an otherwise promising region (History, 2014).

However, the nation has shown positive economic growth over the past ten years, with an annual GDP growth between 4.4 and 10% (UN World Statistics Pocketbook, 2014). Although agriculture remains the primary employment sector, encompassing 65% of the labor force in 2010, employment in the industrial sector has been growing over the past decade. 15.6% of the population lives in an urban area with an annual rate of change (urbanization) of 5.74% (CIA World Factbook, 2014). That means that currently 84.4% of the population lives in rural areas. Access to electricity in rural areas is discussed below.

2.1.2.2 Energy

In 2010 the energy consumption per capita (kilograms of oil equivalent) for Uganda was 38 kg. The US per capita consumption for 2010 was 6501 kg (UN World
Statistics Pocketbook, 2014). Access to electricity for rural communities in Uganda is currently far lower than other nations. About 84% of households are located in rural areas and less than 1% of them have access to modern energy services (Buchholz et al, 2010). The national electricity deficit in 2007 was estimated to be 165 MW. Electricity demand is increasing at around 8% per year (REA, 2007), and around 34% of total investment is currently put into generator backup systems (Eberhardt et al, 2005). The inadequacy and lack of reliability in Uganda’s electrical supply results in lowered economic productivity and missed opportunities for development. Without access to electricity rural communities end up paying high costs for non-renewable, inefficient energy like kerosene and dry cell batteries for lighting and charging of cell phones (Christensen, 2013). Prices for these energy sources calculate to a high rate of $3/Kwh (SharedSolar, 2011), resulting in a scenario where many poor pay more per unit of energy than their more affluent urban counterparts.

Barriers to large scale national grid electrification efforts include lack of infrastructure, high costs of grid connection over difficult terrain, and low demand. Costs to connect rural households to the national grid are estimated around $1,000 per household (SharedSolar, 2011), an unappealing figure to national energy companies.

2.1.2.3 Environment

"The animals have all moved far away--they can't hide in the pine trees," Keweke says. "We used to look for herbal medicines in the forest, but now we can't. There is something that was lost along with those trees. We have lost a big thing."


Population pressures and resulting expansion of forestland has caused a loss of 2/3rds of forest over the past 20 years. In 1990 Uganda reported 5 million hectares of forestland. In 2005 that figure had fallen to 3.5 million acres (Heuler, 2013). Throughout the last several decades deforestation has significantly exceeded reforestation rates, scientists and policy-makers claim largely caused by short-term exploitation resulting from population growth (Struhsaker, 1987). Others point to powerful special interests within the logging and charcoal industries and questionable political relationships with private sector operations (Struhsaker, 1987; Grainger & Geary, 2011; Deforestation, 2003).

While the long-term impacts of these deforestation rates are not yet fully apparent, research has determined the negative environmental impacts of deforestation including loss of biodiversity and forest-reliant economic and social systems, increased flooding, and contributions to global climate change. Tropical forest ecosystems and topsoils are particularly vulnerable to clearing, with shallow fragile
nutrient systems which can take thousands of years to accumulate being eroded in a
decade (Deforestation, 2003).

It is within this political and environmental climate that biomass energy systems are
being introduced. Economic incentives for mono-crop plantation agroforestry to meet
timber and charcoal demand cause competition with land use for agriculture,
conservation, and potentially biomass supply chains. Finding BGE systems which can
create positive synergies with sound environmental management and equitable social
outcomes rather than creating competition for resources, consolidation of wealth at the
cost of small-holders, or environmental degradation. Frameworks for better
understanding these potential synergies and trade-offs encourage transparency in
decision-making, increased stakeholder participation, and more informed decision-
makers.

2.1.3. Biomass Gasification
Biomass gasification involves exposing biomass to high temperatures in low oxygen
environments, causing pyrolysis, a process by which volatile components of a
feedstock vaporize, creating a gas (producer gas) which can be used to power internal
combustion engines, gas turbines, or fuel cells (Larson, 1998). These systems are able
to create electricity at higher efficiencies and lower costs than boiler and steam
systems of comparable size (Larson, 1998). Modern biomass conversion technologies
offer significant improvements in energy efficiency as well as high potential
environmental benefits and relative use flexibility (Johansson & Goldmberg, 2002).

In addition to current uses in large scale scenarios to generate heat, electricity, and
liquid fuels, biomass gasification is being studied as a solution to small scale off-grid
electricity demands. While at a scale below 500kW, current biomass energy systems
remain economically uncompetitive with grid electricity, (In the Muzizi Tea Estate
case study extension of the national electrical grid provided power at $.12-.16/KWh,
resulting in decommissioning of the onsite gasification system (Buchholz et al., 2012),
in nations with poor physical infrastructure prohibitively high costs make grid
extension unlikely. Barriers to rural electrification in developing nations include high
costs of grid extension, large transmission losses, and low peak loads due to small
isolated communities (Buragohain et al., 2009). In these environments biomass
gasification offers an economically feasible, local renewable energy source that can
contribute to environmental sustainability (Gosh et al., 2003).

Case studies have also shown biomass based energy has a vital role in rural life where
agriculture is the principle activity (Gupta, 2003; Demirbas & Demibras, 2007;
Ravindranath & Balachandra, 2009). When comparing alternative renewable energy
schemes for rural electrification, proponents in India note biomass rates higher
because their heavily agricultural society means biomass is uniformly available across
the country. In nations like Uganda where energy represents and expensive import,
and poor infrastructure limits grid extension biomass energy offers an attractive
solution to meeting growing energy demands.
Small scale biomass gasification systems have proven themselves to be both economically and technically feasible in some instances (Buragohain et al., 2009; Furtado, 2012; Buchholz, 2010). However, reaching economic feasibility requires a confluence of factors. The economic viability of biomass gasification energy systems operated by Pamoja has been investigated through two case studies examined in Buchholz & DaSilva (2012). The article examines a 10kW and a 250kW system, providing project background, system operation details including energy output and efficiency information, a financial analysis, employment generation figures, and environmental impact data. A Levelized Unit Cost of Electricity (LUCE) analysis was conducted for BGE systems with 5-40kW systems, finding that higher capacity utilization increases the economy of biomass gasification, with even a 75% load rate unable to compete with diesel alternatives.

According to these studies, effective business models must balance energy demand and system capacity to be successful. Suggestions to increase economic success of these systems include creation of energy service companies, commercialization of heat energy byproducts, and feed-in tariffs to spur investment into technology. Additionally, the supply chain component, which offers significant potential to improve environmental sustainability and economic activity contributing positively to social conditions, when poorly managed can contribute to concentration of economic inequality, resource competition between food and fuel crops and environmental concerns including deforestation.

The fragility of economic viability in these pilot systems and concerns regarding long term environmental and social impacts indicate the importance of 1. firm learning and improvement of operations and 2. Tools for project planning and implementation that can aid informed decision-making to increase project success rates and make informed trade-offs. An efficient and accurate biomass supply assessment framework can provide valuable structure for project planning as well as firm and stake-holder learning.

### 2.2 Goals and objectives

Enterprises implementing bio-energy systems tend to focus on mechanical engineering and electricity distribution challenges. However, the components of a complete bio-energy system include not only conversion technology and energy allocation, but also the biomass supply component. The increased complexity of the supply chain required for bioenergy systems entails increased start-up and ongoing operational costs (Ravindranath & Balachandra, 2009; Gosh et al., 2003; Buchholz et al., 2012). Furthermore, these components are embedded in a broader system within which sustainable management aims to create synergies between environmental, social, and economic factors (Gibson, 2006). Scaling resource demands to the local ecosystem’s carrying capacity, efficient resource use, and fair distribution are therefore essential considerations to unleash the advantage of small-scale bioenergy production (Buchholz and Volk, 2012).

The resulting complexity of a bioenergy system is difficult to manage at a small scale and is beyond the capacity of companies implementing these bio-energy systems,
resulting frequently in project failure (Buchholz et al. 2009). Studies investigating barriers to implementation find non-technical issues, including managing project level context variability, as major obstacles to successful scale-up of the technology (Gosh et al, 2003; REA, 2012). There is a need for efficient yet accurate assessment tools for project site selection and ongoing project monitoring; Tools that are accessible for project staff, manageable, transparent, rely on minimal data collection and analysis yet can accurately represent on the ground conditions relevant to stakeholder decision making.

In this thesis, the C&I framework methodology will be applied to three case study sites. Building on a preliminary sustainability assessment framework (Christensen, 2011; Joerg, 2012) this research will further develop the assessment tool, evaluating and addressing implementation considerations informed by both the theoretical and practical bodies of C & I literature, with an explicit focus on identifying underlying trade-offs across social, environmental and economic considerations for evaluating small scale bioenergy projects.

To enable these research goals, methodologically, the thesis develops and tests an innovative MCDA decision support software tool for Sustainability Assessment framework implementation. Through examination of weighting impacts, uncertainty features, and sensitivity analysis the thesis will demonstrate the use of the developed MCDA model for project level decision making. A model version complete with detailed user interface, Framework User Guide and Toolkit provides support for framework implementation in a wide variety of project level planning scenarios, allowing potential dissemination of the SA framework and MCDA model to a range of bio-energy systems.
Chapter 3  Journal Article

USING MUTLI CRITERIA DECISION ANALYSIS TO DEVELOP SUSTAINABILITY ASSESSMENT TOOLS: BIOMASS SUPPLY CHAINS

Abstract

Sustainable energy access remains a significant challenge in nations lacking resources and strong infrastructure, creating barriers to economic development and increased standards of living. 1.3 billion people lack access to electricity globally (IEA, 2015). Small scale bio-energy systems (10-100kW) have been developed to meet energy needs in rural areas, creating synergies between agricultural and agro-forestry systems through utilization of biomass feedstock for electricity generation (Gosh et al., 2003; Buragohain et al., 2009; Buchholz et al., 2010). The success of such systems requires sophisticated planning and coordination of the biomass supply chain.

Building on a preliminary sustainability assessment framework (Christensen, 2013; Joerg, 2013) this research will further develop an assessment tool designed to capture sustainability requirements of the biomass supply chain in the ecological, social, and economic spheres through testing on three case studies in rural Uganda. The SA tool will facilitate identification of trade-offs and aid decision makers in choosing appropriate scale and technology of small scale bioenergy projects. Among the case study national population of approximately 35 million, about 84% of households are located in rural areas and less than 5% of them have access to modern energy services (Buchholz et al., 2010). When managed well, small scale energy systems can be applied successfully in these and a variety of contexts, providing modern energy services where grid access is not feasible. Overview and discussion of framework implementation through Multi-Criteria Decision Analysis (MCDA) modeling software to plan and monitor project supply chains in multiple contexts will offer valuable insights guiding future framework structuring and use, adding to a growing body of literature supporting sustainable development of biomass energy systems. This will set the stage for a larger research effort in building, implementing, and disseminating a generic sustainability assessment framework for biomass supply chains of small-scale bio-energy systems. In addition, application and analysis of methodologies for project evaluation will contribute to development of strategies for energy system analysis which build stakeholder capacity to incorporate social, economic, and environmental considerations and trade-offs.
Section 1. Introduction

The sustainable development of energy systems is becoming increasingly important as policy objectives seek to incorporate economic development, increased equality, and mitigation of environmental impacts into energy planning (IPCC, 2013; United Nations, 2014; Santoyo-Castelazo & Azapagic, 2014; Amezega et al. 2010; Elliot, 2006).

Environmental Impact Assessment (EIA) is the current accepted strategy for assessing environmental impacts in planning arenas and has been used widely in energy project development scenarios. However, many claim this method is both too narrow and lacks a strategic element, often coming into a project’s development at the final stages of the process (Amezaga et al., 2010; Gibson, 2006; Nobel, 2000). EIA also lacks a social impact component precluding stakeholder discussion of social considerations in project planning. Meeting policy aims to strategically address social, economic, and environmental considerations requires integration of all three aspects of energy systems.

Sustainability Assessments (SA) are being developed to incorporate social, environmental, and economic considerations into decision-making at a strategic level, facilitating deep conversation, meaningful learning, and formulation of explicit, transparent definitions of sustainability goals (Kowalski et al., 2009; Scott et al., 2012; Schenler et al., 2009). Leadership within the European Union and member nations has driven development of Sustainability Assessment frameworks and certification schemes for biomass resources through legislation including the Renewable Energy Directive.

Sustainability Assessment is a relatively new field in energy planning. Wide variations of scope and methodologies are reflected in a number of studies that have considered the sustainability of energy systems (see Santoyo-Castelazo & Azapagic, 2014 Table 1; Scott et al., 2012; Nakata et al., 2011). Improvements and consensus around process and structural elements of frameworks are needed to improve outcomes and reach strong sustainability objectives (Hacking & Guthrie, 2008; Buchholz et al., 2009). There remain few attempts to develop and implement generic planning tools for energy system sustainability planning (Santoyo-Castelazo & Azapagic, 2014) and fewer still focused specifically on decentralized systems for meeting rural energy needs.

Further, current research notes the inherently normative nature of the process of SA, pointing out that creation and implementation of an SA framework is a combination of scientific process and political norm creation (Ramesteiner, 2011). Achievement of strong sustainability principles is not guaranteed through use of accurate data, but is
highly dependent on the decision-makers normative definitions of what exactly “sustainable” means through choices regarding indicator development, differential weights on chosen indicators, scope of framework goals, and decision structuring. Participation and stakeholder inclusion in the creation and implementation process is therefore recommended to create a robust assessment process (Pope & Grace, 2006; Buchholz, 2012). While universal consensus and uniform methodologies are therefore not only impossible but undesirable, a focus on development of decision tools which allow decision makers to inclusively identify and better understand potential tradeoffs has potential to significantly strengthen decision outcomes (Zia et al. 2011, 2015).

This research seeks to build upon the burgeoning SA literature by addressing the research question: How does weighting of criteria and indicators impact decision outcomes given changes in stakeholder priorities? The question is addressed through the presentation and application of an SA framework for bio-energy supply chain management using Multi-Criteria Analysis (MCA) on three case study sites in rural Uganda. Available potential biomass supply options including agro-forestry supply chains and agricultural residues will be evaluated. Our hypothesis used for framework application is that site and supply scenarios implementing agro-forestry practices will score higher when environmental and social criteria are weighed more heavily, and agro-residue supply scenarios will score higher when economic considerations carry higher weights.

Enterprises implementing bio-energy systems tend to focus on mechanical engineering and electricity distribution challenges. However, the components of a complete bio-energy system include not only conversion technology and energy allocation, but also the biomass supply component. The increased complexity of the supply chain required for bioenergy systems entails increased start-up and ongoing operational costs (Ravindranath & Balachandra, 2009; Gosh et al., 2003; Buchholz et al., 2012). Furthermore, these components are embedded in a broader system within which sustainable management aims to create synergies between environmental, social, and economic factors (Gibson, 2006). Scaling resource demands to the local ecosystem’s carrying capacity, efficient resource use, and fair distribution are therefore essential considerations to unleash the advantage of small-scale bioenergy production (Buchholz and Volk, 2012).

The resulting complexity of a bioenergy system is difficult to manage at a small scale and is beyond the capacity of companies implementing these bio-energy systems, resulting frequently in project failure (Buchholz et al., 2009). Studies investigating barriers to implementation find non-technical issues, including managing project level context variability, as major obstacles to successful scale-up of the technology (Stephens et al., 2014; Gosh et al, 2003; REA, 2012). There is a need for efficient yet accurate assessment tools for project site selection contingent upon biomass supply chains as well as for ongoing project monitoring; Tools that are accessible for project
Section 2. Background

2.1 Biomass Gasification for Rural Electrification

Biomass gasification has been established as a feasible energy technology (Jenkins, 2015) and biomass gasification technologies to generate heat, electricity or combined heat and power (CHP) are commercially available at a range of system scales (Peterson & Haase, 2009; Kikels & Verbong, 2011). Gasification has the advantage over combustion of more efficient and better controlled heating, higher efficiencies in power production and the possibility to be applied for chemicals and fuel production (Kikels & Verbong, 2011, Larson, 1998). Biomass energy is further considered cost-
effective compared to wind power projects and does not create theft issues experienced with solar power (find citation?)

Recent concerns regarding GHG emissions and climate change has spurred renewed interest in biomass gasification projects (Peterson & Haase, 2009; Pereira et al., 2011) and European nations have become the leaders in gasification research (Mirata et al. 2005; Kirkels & Verbong, 2011). Additionally, global analysis suggests biomass potentials of 50 EJ (Gregg & Smith, 2010) and global biomass abundance ratings rank the energy source third most abundant behind coal and oil (Periera et al., 2011), suggesting significant potential for renewable technologies that use biomass. National research estimating biomass potential has been conducted in a number of countries (Okello et al., 2013). However, high investment and learning costs in comparison to conventional electricity markets are cited as preventing widespread dissemination of gasification technology (Gosh et al., 2006; Pereira et al., 2011; Kirkels & Verbong, 2011; Larson, 1998). Indeed, available energy alternatives constitute a major factor in competing perspectives regarding economic feasibility for BGE systems (Buchholz et al., 2012).

Their current application, therefore, lies largely at the demonstration and limited production stages; with commercial applications addressing niche markets including rural off-grid electricity markets (Kikels & Verbong, 2011; Periera et al., 2011). Access to grid electricity often renders biomass gasification technology prohibitively expensive in the absence of internalizing economic policies (Buchholz et al., 2012; Mirata et al., 2005) whereas comparisons against diesel alternatives, frequently imported at high costs, point to cost savings for gasification implementation; particularly where inexpensive biomass supplies are available (Larson, 1998 pg 7, Ravindranth & Balachandra, 2009; Buchholz et al., 2012; Fischer & Pigneri, 2011; Stassen, 1995).

While at a scale below 500kW, current biomass energy systems remain economically uncompetitive with grid electricity, in nations with poor physical infrastructure, prohibitively high costs make grid extension unlikely (Buchholz et al., 2012). Rural electrification in these contexts represents the frontline of energy access and economic development. Among rural households electricity ranks second on the list of needs essential to daily life behind only food and housing (Hong & Abe, 2012). Gasification’s ability to operate at the small local scale provides opportunity for success with local level piecemeal energy solutions which William Easterly (2006) adeptly points out often generate the most robust and effective social transitions. Barriers to rural electrification in developing nations include high costs of grid extension, large transmission losses, and low peak loads due to small isolated communities (Buragohain et al., 2009, Buchholz et al., 2012). In these environments biomass gasification offers an economically feasible, local, and renewable energy
source that can contribute to environmental sustainability (Gosh et al., 2003). It is also promoted for its potential positive social impacts due to livelihood diversification and local economic activity production (Fabe et al., 2014).

2.2 Ugandan Energy Context

The assessment framework is applied through the evaluation of four case study scenarios in rural Uganda. Currently Uganda faces a major energy deficit and low rates of electricity access. In 2010 the energy consumption per capita (kilograms of oil equivalent) for Uganda was 38 kg. The US per capita consumption for 2010 was 6501 kg (United Nations, 2015). Biomass represents around 94% of primary energy use and is used mainly for cooking, the production of charcoal, and in small industries (MEMD, 2009). Concerns over high deforestation rates due to heavy reliance on biomass energy and rising populations have spurred research into alternative energy sources including biomass residues (Okello et al., 2013). While oil reserves of at least 3.5 billion barrels were confirmed in Uganda in the Hoima district in 2006, in 2013 petroleum products remained the number one import for the nation costing 1281.1 million US dollars (United Nations, 2014).

Uganda has a nationwide electrification rate of 9% and a rural electrification rate of 4%, among the lowest in the world (IEA, 2011). Current installed electrical generation capacity is 682 MW through hydro, thermal, and bagasse thermal generation systems (ERA, 2012). In the short and medium term Ugandans faces serious challenges in moving forward with increasing centralized generation capacity and improving the state of the national electricity grid (Christensen, 2013).

Over 84% of Ugandans live in rural areas and in most cases it is not cost effective to connect these houses to the grid (Shared Solar, 2011; REA, 2012). Without access to electricity rural communities end up paying high costs for non-renewable, inefficient energy like kerosene and dry cell batteries for lighting and charging of cell phones (Christensen, 2013). Prices for these energy sources calculate to a high rate of $3/Kwh (SharedSolar, 2011), resulting in a scenario where many poor pay more per unit of energy than their more affluent urban counter-parts.

The MEMD and REA in Uganda have recognized that distributed generation from renewable energy sources is the best potential medium-term solution for providing electricity to rural communities. Progress has been slow, but is continuing and there is currently large growth of small scale solar household systems, which include small solar panels for powering a LED lights and charging cell phones (REA, 2007). However, these systems are in the low watt range and are not suitable for large loads in rural areas that are currently being run on diesel engines.
3.1 Case Study Site and Field Work Methods

3.1.1 Case Study Introduction

In 2012 an international group of engineers and entrepreneurs started Pamoja, Cleantech AB; A socially minded business which works with communities across Uganda to operate small scale BGE systems for productive and household use. Over the past three years, Pamoja has gathered funding, developed community relationships, and installed three pilot systems ranging from 10-32KW in the villages of Ssekanyonyi, Tiribogo, and Opit in Central and Northern Uganda. Pamoja hopes to contribute to renewable distributed energy generation by implementing Bimoass Gasification Energy (BGE) systems at the 10-100 kW range which is more suitable for larger loads and whole community power.

The assessment framework is applied using data collected at two case study sites in central Uganda. The choice problem being investigated is the selection of supply chains between sites and biomass supply options. Which site/supply combination is viewed as the best option given certain prioritization of criteria? Tiribogo is a village located approximately 3km from Muduuma, a small town with grid connection along the highway an hour outside of the capital city of Kampala. The Tiribogo site includes a 32 kW Husk Power Systems gasifier which operates 6 hours per day. Ssekanyonyi, another small village outside of Kampala is located 30km from Muduuma, and 20km from grid electricity sources. The Ssekanyonyi site includes a 10 kW gasifier as well as six solar panels and battery storage.

3.1.2 Data Collection

Research was conducted in partnership with local stakeholders as well as field experts, with the learning process from case study application concurrently informing framework development. While secondary data compiled at national and regional levels are used to inform the MCA model (see Table A.1 in Appendix A for a list of data point sources), national infrastructure deficiencies result in dated figures and inaccuracies. Small scale, highly localized systems such as those being studied require localized data difficult to disaggregate from national figures.

Survey data, expert interviews, and field observation provide local level data from direct sources. The survey tool can be accessed in the SA User Guide and Toolkit available online through Pamoja. Surveys were completed in person with the aid of a translator. Survey responses gathered in 2013 by graduate student Lenore Joerg (Joerg, 2013), were combined with surveys conducted during June and July of 2014 for a total of 54 surveys gathered from the Tiribogo site. Ssekanyonyi had no previous
survey responses available. A total of 46 surveys were gathered between June and July of 2014 through in person interviews with translator assistance. Interviews were also conducted with cooperative leadership at both sites including cooperative secretaries and directors. Local officials were also interviewed including village and sub-county political leaders at both Ssekanyonyi and Muduuma. Other interviews and field observation conducted during field work between June and July of 2014 included attending meetings with Pamoja staff, cooperative meetings and focus groups, site visits with project managers and project partners including representatives from Vi Agroforestry, and field observation with an environmental consultant. Additionally some feedback regarding the framework and weighting process was solicited from Pamoja staff and used to inform discussion of further research. Indicator Scores used for analysis are included in Table 2 of Appendix A.

3.2 SA Framework and MCA Decision Tool

3.2.1 Sustainability Assessment (SA) Framework

The SA framework provides a generic tool which can be adapted to a variety of project contexts. It can be used to compare possible supplies within one project site as well as to compare supply systems at different potential sites depending on the priorities of project proponents and community stakeholders (Wang et al., 2009; Santoyo-Castelazo & Azapagic, 2014; and Buchholz et al., 2009). The method for this process draws from the experience and best practices of standards and organizations outlined in Table 3 in Appendix A. The outline for the assessment process is visualized in Figure A.1 of the Appendix A and described in detail through the Toolkit which is available through Pamoja.

The organizational structure of a typical multi-criteria decision is displayed in Figure 1. At the broadest level is the principle or guiding fundamental truth that is the basis for reasoning/action. Level 2 are the criterion; the principle or standard a thing is judged by. Criteria enhance the meaning and operationality of the principle but cannot measure performance. Level 3 represents the indicator level. An indicator is a variable used to infer the status of a particular criterion. These are the variables being measured and quantified.

For the decision model four criteria were selected representing broad categories; Environmental Impact, Social/Economic Impact, Costs/Quality, and Reliability. Figure 2 outlines the criteria and sub-criteria for the SA framework.

*Figure 1 Framework Organizational Structure

*Figure 2 Criteria and Sub-Criteria Visual

The model described below quantitatively measures the criteria and indicators displayed in Figures 3-6 and listed in Table 4 in Appendix A.
Figure 3 Reliability Decision Tree

Figure 4 Social/Economic Impacts Decision Tree

Figure 5 Environmental Impacts Decision Tree

Figure 6 Costs/Quality Decision Tree

The decision tree diagrams above (Figure 3, Figure 4, Figure 5, Figure 6) demonstrate the relationship of criteria, sub-criteria, and indicators in influencing the overall sustainability of various supply chain options for biomass energy systems. Indicator values reflect a quantitative figure based on gathered data, a qualitative score using expert estimates, or a yes or no binary selection. The framework was calibrated for model use by selecting and aligning data points and expert knowledge that can efficiently demonstrate accurate information regarding criteria. Indicator scores are listed in Table 2 of Appendix A. For list of criteria, sub criteria and indicators see Table 4 in Appendix A, for a description of data point measurements and sources at indicator level see Table A.1 in Appendix A, for a description of indicators see the SA User Guide available online through Pamoja. A description of the MCDA methods and model development for framework application follow below.

3.2.2 Multi-criteria Decision Analysis and Decision Tool

3.2.2.1 Multi-Criteria Decision Analysis

The biomass supply chain sustainability assessment framework is applied through decision support modeling software Analytica Professional Version 4.6 using Multi-Attribute Utility Theory (MAUT). MAUT is a method within Multi Criteria Decision Analysis (MCDA or MCA).

The approach has been used successfully in resource management and technology implementation at a range of scales including international, national, regional, and project level decision making (Zia et al., 2011, 2015; Scott et al., 2012; Zhou et al., 2006; Buchholz et al., 2009; Cristobal, 2010; Kowalski, et al., 2009; Buchholz et al., 2009).

Review of current multi-criteria decision-making methodology for bio-energy systems identifies a number of methods and wide range of applications within the field (Cristobal, 2010; Buchholz et al., 2009; Scott et al., 2012; Huang et al., 2010; Goutini & Martel, 1998). For a review of MCA Methods currently applied for energy system planning see Kurka & Blackwood, 2013; Santoyo-Castelazo & Azapagic, 2014 ). For this case study assessment the Multi-attribute Utility Theory (MAUT) method from within Multi-Attribute Decision Making (MADM) is used to compare alternative supply options through scoring and weighting of environmental, social/economic, and financial criteria. MADM is characterized by a small number of possible alternatives...
with the best alternative selected by comparing alternatives with respect to each attribute (Cristobal, 2010).

Multi-attribute utility theory is applied using the SMART (Simple Multi-Attribute Rating Technique) (Goodwin & Wright, 2009) method. The SMART method is widely applied because of its relative simplicity and transparency, allowing participants from a wide range of backgrounds to easily accept and understand recommendations (Kurka & Blackwood, 2013; Goodwin & Wright, 2009 pg 34) and ensuring stakeholder participation in structuring problems, identifying stakeholder value preferences and trade-offs (Gregory et al. 2001; 2012).

3.2.2.2 Model Mechanics

A decision support model was designed using Analytica decision support software informed by the revised assessment framework. Analytica model is available upon request; and can be made available as an online web-based application. The model implements weighted summation through the SMART method to compare alternate scenarios, allowing users to input scores and weights for each indicator (Kurka, 2013; Liu, 2014; Goodwin & Wright, 2009). Within the MCDA model vector normalization is used to normalize scores and weights; the model normalizes all value inputs on a scale between 1 and 100 based on a best and worst scale set by stakeholders. Table A.1 in Appendix A outlines indicator rating methods, scales, and sources. Decision makers assign a weight to each indicator and criteria at all levels of the decision tree. Indicators normalized using vector normalization are then weighted and summed to produce overall scores for each sub criteria level. These sub criteria are again weighted, summed and normalized to aggregate scores at the criteria level. See Table 1 for a list of equations used to normalize and aggregate indicators and criteria and Figure 7 for a mechanics visual. If/then statements are included to address zero scores in normalization.

Table 1 Equations for Normalization and Scoring

Figure 7 Model Mechanics

3.2.2.3 Case Study Application

Weighting

The model runs one supply option and weighting scheme at a time. Model versions were developed for each of three expert weighting schemes. Weights were supplied by three experts representing different priorities and expertise. An environmental consultant provided weights from a strict environmental prioritization perspective. A project developer provided weights from the perspective of a business implementing bio-energy systems, and a development expert provided weights from the perspective of an economic growth oriented international development expert working in
developing countries with some interest in environmental and social sustainability. See Table 2 for a list of criteria level weights provided by each perspective. Weights provided for case study application are meant to provide working examples in order to demonstrate the uses and features of the decision process rather than provide analysis regarding the case study sites.

Table 2 Criteria Weights by Expert

The three expert weighting schemes were applied to indicator level scores from two case study sites, examining two supply options at each site for a total of four case study scenarios.

Criteria scoring by site and supply chain

Scores for each of the four supply scenarios were obtained through expert input, secondary data sources, as well as surveys and interviews. Table A.1 in Appendix A provides details regarding sources and rating methods for all criteria. Scores are held constant across weighting scenarios to examine how weighting impacts overall criteria performance. Table A.2 in Appendix A lists the scores used for weight comparisons. A more detailed description of the highlights listed in Table A.1 in Appendix A, including assumptions and uncertainties for each indicator, are available in the SA Framework under a subsection Case Study Methods within each criteria section available through the Pamoja website.

3.3 Model Assumptions and Limitations

3.3.1 Assumptions

SE2.2.1 Percentage Use of Supply, SE2.2.2. Threshold (see Table A.1 in Appendix A)

No questions regarding alternative uses for trees within new agroforestry systems were asked through the survey tool. Alternative use was therefore assumed at 50% which is comparable to maize cob use as observation and interviews suggested trees were already being used for alternative uses despite their relative newness. Future surveys should ask if there are competing household uses for agroforestry products as well as maize cobs.

E6. Carbon Cycle (see Table A.1 in Appendix A) Carbon neutrality was assumed if competing use and leakage scores are low risk.

CQ1. Costs

Costs for “supply” and “processing” for agroforestry system is unknown because this is a new system. They are assumed to be 0 in Site 1, Tiriibo, as there is no payment for supply at that site and 50ugx/kg in Site 2, Ssekanyonyi, because Pamoja was
paying that price for cobs so an expectation of payment for supply has been set. The cost of processing is listed as zero as it was assumed to be a part of the maintenance position. The cost of transportation for agroforestry systems were assumed to be the same as the maize costs listed by Pamoja management.

3.3.2 Limitations
The model was built to run one scenario at a time. This greatly increases the data input and output requirements for comparison of multiple scenarios. The model software also does not easily visualize results, further adding to the time needed to extract and communicate results to decision makers.

This model also represents a deterministic scoring scenario. Using stochastic score inputs, a key feature of the Analytica software program, would improve understanding of uncertainty within the model, which is important when quality data availability is low.

Section 4. Results

4.1 Weighting Impacts on Criteria and Scenario Scores

Figure 8 Criteria Weights by Expert

The weights selected by experts (Figure 8) appear representative of the criteria priorities most valued within their respective fields. Again weights and scores used for case study application are for demonstration. Weights above are meant only to provide examples and to demonstrate the decision process and tools. They can be changed easily as data availability and expert opinion dictates.

4.1.1 Scenario Rankings by Expert

Figure 9 Scenario Rankings by Expert

The scores between scenarios in each weighting scheme are all within a close range of final weighted scores and total scenario sum scores further show overall consistency (Figure 9), indicating normalization and summation techniques are accurately assessing scenarios.

The rankings of each scenario according to weighting schemes, as displayed in Figure 9, show that weight has an impact on the selection of most sustainable scenario. For this case study, rankings indicate that Scenario Four Ssekanyonyi Agroforestry represents the most sustainable supply for both the environmental and business
weighting schemes. It scored second in the economic development weighting scheme, possibly due to lower weights assigned to environmental criteria in which Scenario Four scored more highly. The lower ranks show a diverse range of results with no clearly superior scenario across weights, indicating the weights assigned to criteria and indicators does have a significant impact on the selection of most sustainable scenarios.

4.1.2 Criteria Scores and Weighting

Figure 10 Site 1. Tiribogo Criteria Scores by Expert

Figure 11 Site 2 Sekanyonyi Criteria Scores by Expert

Figure 10 and Figure 11 display the criteria scores by weighting scheme for each site. Scores for each scenario were kept constant and weights were applied representing the three “sustainability perspectives” referenced above (Figure 8). The environmental expert gave zero weight to other criteria therefore the environmental criteria were solely responsible for the scenario scores. Environmental criteria scored low in the development expert weighting scheme, it received only 10% of the final criteria weighting, and therefore we see low final criteria level scores at both sites.

Also, while both the project manager and development expert gave the reliability score 30% of the final weighting, their final weighted scores are different. Reliability scores are higher for the development weighting scheme. This is due to different weighting within the criteria at the sub-criteria and indicator levels and demonstrates the importance of further analysis of the development of criteria level scores.

4.1.3 Sub-Criteria and Indicator Level Scoring and Weighting

Weighting of Reliability shows that the criteria were weighted equally by both the development and business expert at 30% of the final scenario score (Figure 8). However we see that the weighted scores for that criteria vary significantly (Figure 10, Figure 11). Reliability has a higher final score for the development expert than for the business manager. Understanding the differences in these final scores entails analyzing the differences in weighting and scoring within the criteria at the sub-criteria and indicator levels. The Analytica model allows decision-makers to pull figures for scores, weights and weighted scores at all levels of the decision tree. An example analysis of the Reliability Criteria scores is provided in Appendix B.
4.2 Stochastic Scoring Probability Distributions

Figure 12 and Figure 13 display probability distribution results for R1.1 indicators.

Figure 12 Years in Operation Probability Distributions

Figure 12 demonstrates a probabilistic representation of R1.1.1 Years in Operation. Rather than inputting a single deterministic estimate for a figure, Ananlytica allows use of probability distributions. A triangular distribution is used here to more accurately display the uncertainty around the score. The range of possible years in operation for Tiribogo Maize is between one and three years, with higher probability that one year is the correct estimate. Similarly, the Tiribogo Agroforestry scenario has a slightly higher uncertainty, ranging from zero to three, and also has the highest probability of one year in operation. The Ssekanyonyi sites both demonstrate a lower level of uncertainty through a shorter probability range of only one year, from 9 to 10 years with the highest probability at the 10 year mark. These graphs demonstrate there is more uncertainty regarding the variable at the Tiribogo site, however the uncertainty level for this variable is not problematic.

Figure 13 Productivity Probability Distributions

Note. u = micro \((10^{-6})\), m= milli \((10^{-3})\).

Figure 13 displays stochastic results for R1.1.2 Productivity. For the Tiribogo maize supply we see a probability range of 250 to 2000 kg/yr with the most likely correct estimate falling around 1600 kg/yr. For the Tiribogo agroforestry supply we see a higher range of uncertainty, from 0 to 5,000 kg/yr. The most likely is lower than the mid-range, at 1,500kg/yr. For Ssekanyonyi maize cobs the probability range is again between 250 and 2000 kg/yr, however the most likely estimate for this supply chain is higher than for the Tiribogo site, at 2,000 kg/year. The Ssekanyonyi agroforestry system has a higher overall probability range than Tiribogo and less uncertainty with a possible productivity of 1,000–2,400 kg/yr and most likely estimate of 1,500 kg/yr.
4.3 Sensitivity Analysis

Figure 14 Tornado Analysis Development Weighting Scheme 80-120% Variation

A tornado analysis was conducted for the development weighting scheme for ‘Site 1 Tiribogo Maize Supply Option’. This sensitivity analysis graphs the impact a change in indicator level variable scores has on the overall criteria score. A large range demonstrates more sensitivity to score changes, indicating a variable is important to the criteria level score. The reported variable behaviors were observed at a variation range of 80% to 120% for the development weighting scheme (Figure 14); asking what change in the criteria score would result due to an indicator score at a low of 80% its original level to a high of 120% of its original value. At this indicator score variation level none of the criteria scores changed by more than a few points for either weighting scheme. However as overall model scores were close (Figure 9), these variations are significant and need to be taken into account when considering the model results.

A detailed comparison of criteria sensitivity between weighting schemes is provided in Section B2 of Appendix B to demonstrate how indicator importance changes given different weighting schemes. Furthermore a sensitivity analysis at the 40-160% range demonstrates that when more uncertainty is present in the model (See Figure B.1 in Appendix B) we see these ranges increase substantially.

4.4 Radar Graphs

Figure 15 Radar Graphs

Radar graphs allow stakeholders to visualize criteria performance in relation to other criteria and is useful for understanding trade-offs occurring in each scenario. For this case study we see in Figure 15 above that the project manager weighting scheme shows agroforestry at both sites is receiving high scores in the environmental criteria. Both maize and agroforestry score relatively well in costs/quality and social/economic impacts, and poorly in reliability for both sites in the project manager scheme. At site one maize cobs scored slightly higher than agroforestry in social/economic impacts however at site two the reverse occurred.

For the environmental expert all of the weighting and scoring occurs through the environmental criteria, which is represented in the radar graph.
The development weighting scheme results in low environmental scores and higher reliability scores for both sites and supply chains. We see agroforestry scores slightly higher at both sites in environmental criteria and at site one in social/economic impacts.

**Section 5. Discussion**

5.1 Expert Weighting and Scenario Scores (see 4.1 Weighting Impacts on Criteria and Scenario Scores, pg. 32)

The determination of weights at all levels of the decision tree has a significant impact in the final sustainability score of the supply chains. Different weighting schemes representing differing perspectives on the meaning of “sustainable” will result in the selection of different supply systems as most sustainable when variable scores are held constant.

There also appears to be a level of variability between sites within the same weighting scheme. For example under the environmental perspective weighting scheme the agroforestry system in Ssekanyoni scored the highest at 53.04 while the agroforestry system in Tiribogo scored the worst at 44.9 (see Figure 9). This indicates the importance of system context in determining the most sustainable system, and highlights that changing contexts impact the sustainability from site to site. A supply chain that works well for one site does not necessarily work best for another even when priorities remain the same.

5.2 Detailed Scoring and Weighting Breakdown (see in B.1 Criteria Scoring Analysis in Appendix B)

The model allows users to conduct detailed analyses of criteria, sub criteria and indicator scoring and weighting interactions through a detailed interface. This could provide useful for better understanding interactions between sub criteria and aligning resources with priorities.

5.3 Sensitivity Analysis

Sensitivity analysis provides a variety of information. Within a weighting scheme it demonstrates which variables are most important, which can allow users to focus resources on gathering accurate data for more important indicators. Across weighting schemes it helps stakeholders understand how weighting is impacting the importance of variables in determining final criteria scores. This can be useful in understanding how preferences and definitions of “sustainable” through preference weighting impacts the importance of variables.
5.4 Model application to decision making

Combining the uncertainty analysis through the stochastic scoring of indicators with the sensitivity analysis of the Tornado Diagrams can assist decision-makers in accurately understanding the confidence levels of the model results as well as determining important variables and target limited resources.

For example, the Tornado analysis of the business perspective weighting scheme allows the user, a project planner or project evaluator, to see that of variable ‘R1.1 supplier reliability’, the indicator ‘finances’ is the most impactful on changes to the overall ‘Reliability’ criteria score (Figure 14, pg. 35). The stochastic score of the ‘R1.1’ variable (Figure 13, pg. 34) shows that there is a very high range of uncertainty for the ‘productivity’ variable at the Tiribogo site, and still a wide range of uncertainty at the Ssekanyonyi site. Especially due to the importance of this variable the high uncertainty level indicates resources should be moved from gathering data on less impactful indicators to reducing the uncertainty of the more important variable.

Well calibrated and highly accurate models rely heavily on the availability of frequency data as well as research informing development of indicators and model structure. The lack of institutional and private sector infrastructure in some countries limits access to information with which to build and calibrate a model. Probability distributions and sensitivity analysis can allow models to more accurately reflect the knowledge we have about a subject, but without good data that knowledge retains a high degree of entropy and is less useful for predicting outcomes (Chrisman, 2008).

5.5 Further Research

There is a significant amount of qualitative scoring for observations that are not able to be quantified by collected data. This could indicate a need to select more measurable criteria and indicators, or a preference for expert opinion over figures that are not easily calibrated, a common issue with data collected in contexts with lack of available quality data. In this instance expert estimates can be useful and more accurate, especially when subjective probability distributions are used to incorporate uncertainty and probability distribution assessments are conducted to calibrate expert estimations which often suffer from cognitive biases including overconfidence (Goodwin & Wright, 2009; Chrisman, 2008). However, Pamoja staff reported feeling ill-equipped to accurately estimate some of the indicator scores, demonstrating a need to find additional expertise or data sources especially for environmental indicators. Important insights from the site communities are also minimally included at this point in the MCDA process. Now that framework indicators have been more clearly defined through model and case study implementation there is a need to align data collection to improve the accuracy of scores and increase representation from stakeholders.
While a number of criteria were synthesized and measurement techniques improved through the implementation process, a small scale system with potentially lower available resources for project planning highlights the importance of identifying fewer key indicators for analysis. The project manager indicated feeling some indicators and criteria seemed to overlap, and too many indicators can dilute the precision of data collected. A structural recommendation for further development of the generic framework be is to use sensitivity and uncertainty analysis to simplify and synthesize indicators and criteria.

A process related recommendation is to conduct synthesis and indicator development before reaching the model creation stage. Hone data points to 25-30 indicators that best communicate the priorities needing consideration; enough to make an accurate decision without overcomplicating the system. The goal for system planning must be to create a useful tool rather than detracting from the decision process. A simple exercise using Analytica to understand how weighting of priorities impacts indicators could help determine important variables as well as highlight differing priorities among stakeholders.

Additionally there is a need to incorporate further stakeholder participation. A cross sectional review of small scale rural electrification projects found project sustainability beyond initial implementation contingent on the following factors

- Local availability of maintenance and repair service
- Trust and reliability between implementing organization and other stakeholders
- Sense of ownership among beneficiaries was critical, particularly in community projects
- User satisfaction with technology (Terrapon-pfaff et al., 2014)

Soliciting weighting schemes from local cooperative members and political leadership can help address authentic stakeholder participation. With proper introduction to the weighting process their input can highlight the priorities valued within the receiving environment.

Sensitivity analysis should be used to determine impactful indicators and criteria, and stochastic modeling can further inform stakeholders regarding uncertainty within the decision. This additional research will improve understanding of the current areas of uncertainty, allowing that to be incorporated into decision-making as well as used to inform resource prioritization regarding important indicators and data collection.

Some research find that often the highest scoring scenario would be selected across a multitude of decision tools when similar scoring and importance values are given to criteria (Kurka and Blackwood, 2013). Frequently it takes large variations in indicator scoring for alternate scenarios to be selected. However, some research has found use of different decision tools resulted in different preferred scenarios being selected.
Another calibration process could be to evaluate scenarios using other modeling software and compare results.

5.6 MCDA as a decision tool

MCDA literature is careful to clearly define best practice in the use of MCDA, and dispel common myths regarding its capabilities and purpose. As Belton states “The aim of MCDA should be, and principal benefit is, to facilitate decision makers understanding of the problem faced, about their own, other parties’, and organizational priorities, values, and objectives, and through exploring these in the context of the problem to guide them in identifying a preferred course of action” (Belton and Stewart, 2002). Results highlight that this model is able to provide valuable information to educate decision makers in comparing the sustainability of supply chain options as well as understanding their subjective priorities and how differing goals impact the definition of sustainability within the system.

The results also demonstrate that the value of MCDA lies within the process rather than any prescriptive recommendation. The MCDA process enables elicitation of trade-offs and quantitative comparisons for implementing Sustainability Assessments. It also effectively highlights differences in priorities among stakeholders in defining sustainability. Critiques of MCDA claim it is a prescriptive approach, prohibiting the nuanced understanding required when considering complex problems. French, in response, describes decision analysis as a delicate and subtle tool that helps decision makers better understand their beliefs and preferences, provides a language and formalism for the decision process, and facilitates communication between stakeholders (French, 1989).

5.7 Usefulness vs Usability

The framework development and research process for tool application also highlights a tension between research and application requirements in usefulness and usability. Usefulness refers to the ability to use the product of research in making generalizable claims and requires a robust, rigorous, exhaustive process. Usability refers to the ease of application by practitioners in the field for planning, evaluation, and decision-making.

A key strength in the usability of the presented generic SA tool is its ability to be taken and adapted for many projects using biomass supply chains. Indicators can be added or removed and figures can be changed to reflect site contexts. The Analytica model can be made available online or adapted for specific decision making by EU projects requiring SA in planning, as well as other bilateral and multilateral donor agencies that are engaged in economic development and can potentially use such a tool to identify sustainable scenarios for bioenergy projects.
This project further highlights long standing tensions between academic research and practical application. The academic role in generating rigorous, robust information for practical use against a practitioner need to find and use relevant information efficiently exposes issues around resource allocation, adaptive management as well as achievement of accuracy and precision in knowledge generation. The tools developed through this research aim to provide an accessible yet sufficiently accurate research process for evaluation and planning of biomass supply chains. The tools can also be simplified for use in examining differing priorities among stakeholders and how changing perspectives impact conclusions about the best alternative.

Section 6. Conclusions

The SA framework for biomass supply chain planning accompanied by the MCA decision software is a useful tool for increasing stakeholder understanding of project level criteria. This research demonstrates Analytica decision software offers a number of valuable ways to display and analyze data for informing sustainability assessments including sensitivity analysis, uncertainty analysis, information on sub-criteria and indicator level scoring, as well as weighting analysis. Results indicate that understanding sub-criteria level scoring is important to fully understand final criteria level scores. The decision tool does allow for more detailed analysis within and across weighting schemes although the current process is resource intensive. These tools offer ways to break sustainability concepts down into measureable indicators that can be compared, make priorities and subjectivities explicit, and generate better informed and transparent decisions regarding supply chain selection and management in bioenergy systems. The tools developed can be adapted and useful to project planners, donor organizations, and program evaluators.

The MCDA decision tool offers a useful way to apply the Sustainability Assessment Framework In comparison to alternative modeling methods which often require more exact estimations and are less able to explicitly incorporate uncertainty, MCDA allows the identification and consideration of important factors across social, economic, and environmental spheres that can accommodate qualitative analysis and uncertainty. It can produce useful information through the decision support process, and does not require high levels of accuracy within data but can be used with qualitative assessments and still be an extremely useful exercise. As mentioned above the key strengths in this methodology lie in the process of developing and using the structure, which means it can be a useful tool without the need for excessive investments of resources and time.

However, the complicated nature of the analysis does impact its usability, or ability to be accessed by practitioners. Pairing the Sustainability Assessment with the MCDA decision tool increases the amount and accuracy of information informing the decision
process and develop results with academic rigor and therefore useful for knowledge
generation, academic debate, and potentially donor project evaluation; however
qualitative assessment of the criteria laid out within the SA tool in the form of a report
may achieve similar results better suited to the resources and accessibility of
practitioners.

In MCDA simple models useful to the decision process emerge from distilling key
factors in a transparent way that generates better understanding (Belton and Stewart,
2002). The complexity, rigor, and highly involved learning process inherent in this
“science of synthesis” should not be understated as simplicity serves a purpose of
refining the decision problem, informed by participatory learning during model
generation itself.

The process leading to clear and simple models brings us to an important
consideration for MCDA for use in resource poor contexts. Important factors when
evaluating methodologies for use in emerging economies and small scale systems is
availability of resources, data, and inclusion of local stakeholders (Anadon et al.,
2014). MCDA as a field can be highly technical, frequently employing experts with
high levels of training from countries with developed Management Science and
Systems programs. These projects therefore can become resource and time-intensive.
They can also suffer from lack of authentic relationship building and local capacity or
expertise and can be challenging for local private and public entities to implement
well. The extent to which the decision tool and process can increase understanding,
engage, and facilitate communication between receiving communities and project
developers can also significantly impact a project’s success (Terrapon-pfaff et al.,
2014). Using this framework and assessment tool as a way to connect suppliers and
electricity customers has the potential to increase their awareness and buy-in to the
energy system. Identifying important indicators and reducing superfluous variables
can help focus the process.

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A.1 Model Inputs

*Table A.3 Model Rating Methods, Source Details and Scaling*

A.2 The Sustainability Assessment Framework

The SA framework used for case study application is developed and adapted from the framework initially developed by Christensen (2012) and Joerg (2013), which draws ideas and inspiration from many different sustainable biomass and fair labor standards listed in Table A.3.

*Table A.5 Standards Considered in Framework Development*

In drawing ideas from the body of existing sustainable biomass standards, the framework authors synthesized a wide range of criteria for a sustainable biomass supply, guided by considerations relevant to small scale rural energy projects including data availability and resource efficiency. The framework and user guide are available for public use on the Pamoja company website.

*Figure A.16 SA Process Visual*

*Table A.6 Framework and Model Criteria, Sub-criteria, and Indicators*
Article Appendix B. Results Appendix

B.1 Criteria Scoring Analysis

Visualizing the Reliability Criteria decision tree (Article Figure 3) we will start by examining the weights and resulting weighted scores for the sub-criteria R1, R2, and R3.

Figure B. 1 Business Expert Weighting of R1, R2, R3

Figure B. 2 Development Expert Weighting of R1, R2, R3

Figure B. 3 Business Expert Reliability Score Breakdown by Sub-Criteria

Figure B. 4 Development Expert Reliability Score Breakdown by Sub-Criteria

Figure B. 1 and Figure B. 3 show the weights given by the Business Manager to each of the three sub-criteria which make up the final Reliability Score as well as the final weighted scores for each of those categories given that weighting (Figure B. 3).

Figure B. 2 and Figure B. 4 show the weighting given by the development expert for each of the three sub-criteria which make up the final Reliability Score as well as the final weighted scores for each of those categories given that weighting (Figure B. 4). We can see that R2, Supply Dynamics received only a small portion of the weighting from the development expert, 10%, and as might be expected resultantly scored low as compared to the business expert’s final weighted score for that same sub-criteria. We also see that R1, Supplier Reliability was weighted similarly for both experts at 40% and 50% respectively, however there is high variability in these scores across weighting schemes. This prompts us to explore the R1 sub-criteria in further detail.
From the figures above we see that R1.1 Level of Organization was given the same weighting by each expert, resulting in a similar range of scores for that sub-criteria. R1.3 Supply Contract did not contribute to scores for either weighting scheme, indicating no contract was signed and the score for that sub-criteria was approaching zero. R1.4 Supplier Proximity received higher weighting from the development expert at 40% of the final score in comparison to 20% for the business manager. The high score in this sub-criteria contributes to the higher overall score for the R1 Supplier Reliability sub-criteria in the development weighting scheme. We see for the business expert the R1.2 Supplier Numbers is weighted more heavily at 30% as compared to 10% of the development experts weighting. R1.2 therefore constitutes a larger share of the final R1 score for the business expert weighting scheme, however with lower scores within that more highly weighted sub-criteria we see that the business manager’s final R1 scores are lower. This indicates that the sub-criteria being selected as more and less important in supplier reliability have a significant impact on the final criteria score. It also identifies which sub-criteria are impacting the criteria score for each weighting scheme and in what way they are altering the criteria score.
B.2 Tornado Analysis Criteria Sensitivity Comparison

Figure B. 9 Tornado Analysis Business Weighting Scheme 80-120% Variation Range

Figure B. 10 Tornado Analysis Development Weighting Scheme 80-120% Range

Figure B. 11 Tornado Analysis Development Weighting Scheme 40%-160% Variation Range

B2.1 Reliability

Development Weighting Scheme (Figure B. 10)

For this weighting scenario we see that the crop productivity changes has the widest range of impact change on overall reliability with indicator score changes creating scores ranging from 45.8-50.8. Storage capacity and variables related to other uses are the next most impactful on the overall reliability score. We can also see that the signing of a contract and the sales trends in competing markets have minimal impact on the reliability score in this weighting scheme.

Business Weighting Scheme (Figure B. 9)

For the business manager weighting scheme the number of harvest seasons per year has the most significant impact on the final criteria score with an ability to shift the score between 37.5 and 40. Harvest seasons per year is followed by storage capacity and competing use variables for most significant impact on overall Reliability scores. A contract and the group productivity have minimal impact in this weighting scheme.

B2.2 Social/Economic Impact

Development Weighting Scheme

Competing demand holds by far the largest influence range for social economic impacts, with a score range of 46 to 50.5. The amount of supply feedstock reported being used for personal use (47-49.5) also has a significant impact on the social/economic impacts of the supply chain. Current data collection tools do not adequately address these related questions and these variables should receive more resources and focus during project evaluation. Changes in earnings per farmer, income variables and land-use change however appear to have very little impact on the overall social/economic criteria. This could be indicative of the relatively little additional income created by the project supply chain specifically. A full project
analysis would address other social and economic impacts caused by the installation of a system including behavior changes and equality.

Business Weighting Scheme

For the business weighting scheme competing demand variables also held the most impact on the final SE score, however the impact is less for the business weighting scheme (40.5-42.8, a three point spread), than for the development weighting scheme (45.8-50.5, a five point spread). Number of farmers participating was the third most impactful indicator.

**B2.3 Environmental Impact**

Development Weighting

At this weighting scheme all indicator level variables impact the Environmental criteria score by at most just over one point. Changes in byproducts mitigation, supply chain certainty, and the use of native species scores appear to generate the largest range of variation in the overall environmental impact score at about a one point range.

Business Weighting

The business weighting scheme causes indicator level score changes to have an increased impact on the overall environmental criteria score. In this scheme supply chain certainty and byproducts mitigation have the most impact on the criteria score. The number of nitrogen fixing trees and variables related to sustainable farming trainings have the lowest impact.

**B2.4 Costs/Quality**

Development Weighting

Unsurprisingly, total system costs create the highest score variation for this criteria generating a score range of just over 67 to just over 71 pts. This indicates the variable is extremely important in determining the overall Cost/Quality Score and indicates time should be spent ensuring that data point is accurate. Processing costs and energy density of the feedstock also have the potential to change the score by a few points overall.

Business Weighting

Again total system costs has the most impact on the overall CQ score. This is followed by capitol costs, which has the ability to shift the criteria score by three points at this variation level (71.5-74.5).

Increased Uncertainty
At more significant percentage changes, indicators demonstrated higher impacts on overall scores (Figure B. 11), indicating that at higher levels of uncertainty, as demonstrated by higher percentage change ranges, there are larger possible ranges in criteria scores and overall scenario scores. This indicates the level of confidence decision-makers can have regarding overall model scores, allows them to better understand and incorporate uncertainty into their decision-making, and indicates where resources could be targeted to increase model precision regarding important variables to improve the accuracy of the model.

Chapter 4 Sustainability Assessment and User Guide

The following documents include the Sustainability Assessment Framework for Supply Chain Management of Small Scale Bioenergy Projects as well as a User Guide and Toolkit for framework implementation and accompanying appendices. The current iteration of the SA Framework has been adapted from previous research (Christensen, 2012; Joerg, 2013). The User Guide and Toolkit has been compiled through my experience applying the framework and is a preliminary tool for framework implementation.

The guide is aimed at any user looking to conduct an assessment and could be useful to academic researchers, project staff, or donors interested in assessing supply chains for biomass energy systems.

The Framework and Guide will be available via the Pamoja Website. As stated in the Framework introduction replication and adaptation of the tools are encouraged with proper citation.
Biomass Supply Chain Sustainability Assessment Framework for Small Scale Bio-energy Systems

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Authors:
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Stephen Christensen

Framework Version 2
11/2015

Pamoja is a for-profit social enterprise working in the field of rural decentralized renewable energy solutions. We solve some of the most pressing Energy needs for Rural BoP (Base of the Pyramid) people in East Africa, starting with Uganda. Pamoja uses biomass gasification as a platform to enable various energy services.

Suggested citation for framework use:

Introduction

When implementing new biomass supply chains to electrify rural communities, Pamoja is considering a variety of different biomass supply options and management schemes. The best of these supply options is chosen based on weighted sustainability criteria to ensure reliability, maximize social benefits for the farmers and community, minimize negative environmental impacts, and reduce cost.

The following framework provides the steps and guidelines followed by Pamoja in determining the sustainability of biomass supply options. Criteria covering areas of reliability, social benefits & impacts, environmental impacts and costs have been identified to rate the long-term sustainability of the biomass. This framework is meant to serve as a guide for planning and monitoring the biomass supply of bio-energy systems. The ideas may be taken adapted for use freely with proper citation.

This framework is accompanied by a manual which offers guidance on framework application. Decision support software is being developed to assist in the logistical organization and comparison of criteria performances.
1 ASSESSMENT BOUNDARIES

Spatial boundary: These criteria are applied to the community level. Anything that happens outside of this boundary is addressed through leakage effects

Temporal Boundary: The timescale considered for this framework is 10 years, which reflects the projected lifespan of these projects. Data collected should reflect a 10 year outlook when available.

Within the 10 year temporal scale, short and long-term supply options might differ. For instance, Pamoja might consider buying firewood from local farmers during the first year of operations while building an outgrower network that would then provide the system with agroforestry-derived fuelwood starting in the second project year.

2 MAPPING RECEIVING ENVIRONMENT

The initial step in applying the assessment framework is mapping the receiving environment. This could be accomplished through a short report about the area to be assessed, including background information, availability of data. The step should aid in developing an assessment strategy, connecting with the community and area to be assessed, identifying opportunities or constraints, and discussing tradeoffs or thresholds. For example, Pamoja will not accept a project which requires over 45% of residue supply from existing supply.

Key information for mapping receiving environment:

- Local population
- Existence of cooperative
- Community leadership: who they are, responsiveness, reputation
- Other relevant organizations/businesses active in area
- Major crops and estimated average annual yields

---

1 See leakage criteria addressed in SE2. Resource competition, E1. Deforestation, and E.8 Carbon cycle.
3 BIOMASS DEMAND AND SUPPLY ASSESSMENT

The next step in assessing the sustainability of a potential feedstock is determining the total quantity of biomass that will be needed to meet the demand for the system.

3.1 CALCULATE ENERGY DEMAND

This can be done through investigating the existing and potential energy markets through a calculation of current energy use in the area, population dynamics, as well as a community needs assessment. Develop an understanding of the kinds of energy used in the community, for what purposes, in what quantities and at what costs; Cooking, agricultural processing, lighting, entertainment etc. This assessment should take into account variability in load demands, both throughout the day and throughout the year. See table one below for potential energy demand sources.

Table 1.

Possible sources of energy demand

<table>
<thead>
<tr>
<th>Source</th>
<th>Current diesel energy use for electrical or mechanical use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>agricultural processing</td>
</tr>
<tr>
<td></td>
<td>generators for entertainment, business, lighting</td>
</tr>
<tr>
<td>Unmet energy demands and ability to pay</td>
<td></td>
</tr>
<tr>
<td>Business demand</td>
<td>Restaurants</td>
</tr>
<tr>
<td></td>
<td>Shops</td>
</tr>
<tr>
<td></td>
<td>Schools</td>
</tr>
<tr>
<td></td>
<td>Healthcare facilities</td>
</tr>
<tr>
<td>Household demand</td>
<td>Lighting</td>
</tr>
<tr>
<td></td>
<td>Phone charging</td>
</tr>
<tr>
<td></td>
<td>Television</td>
</tr>
<tr>
<td></td>
<td>Refrigeration</td>
</tr>
</tbody>
</table>
3.2 DETERMINE ABILITY TO PAY

While energy demand may be high, and a high number of potential uses for electricity identified, ability and willingness to pay for electric services must also be considered to estimate the load demand that can be expected.

Gathering information on current energy expenses, specifically expenses related to energies which could be replaced with electricity services, can indicate current levels of spending on energy at a site and inform predictions about willingness to pay for electrical services.

For example, Pamoja pilot sites were situated in locations with energy demand for agricultural processing which was being met by costly diesel engines and could be provided by Pamoja at a lower cost/kWh.

3.3 DETERMINE REQUIRED BIOMASS

Energy demand can then be used to calculate the required amount of biomass to meet the energy needs of the community in question. This assessment should also accurately reflect the management scheme or business model being used for the system. Questions to consider when determining biomass demand include biomass type and conversion efficiencies - determining energy produced per volume or weight of the available supply. The following table offers information on the (Lower Heating Value) LHV of various potential biomass sources.
Table 2.

Heating values and conversion figures for biomass feed-stocks

<table>
<thead>
<tr>
<th>Crop</th>
<th>Type of residue</th>
<th>LHV (MJ/kg)</th>
<th>Calorific Value (cal./kWh/kg)</th>
<th>Moisture Content (%)</th>
<th>Ash Content (%)</th>
<th>Bulk Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>Stalk</td>
<td>16.3</td>
<td>4.5</td>
<td>3.89</td>
<td>2.2-2.5</td>
<td>170-185</td>
</tr>
<tr>
<td></td>
<td>Cobs</td>
<td>12.6</td>
<td>3.5</td>
<td>11.5-13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>Straws</td>
<td>8.83</td>
<td>2.5</td>
<td>11.5</td>
<td>21-22.5</td>
<td>120-135</td>
</tr>
<tr>
<td></td>
<td>Husks</td>
<td>12.9</td>
<td>3.6</td>
<td>10-10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beans</td>
<td>Trash</td>
<td>14.7</td>
<td>4.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundnuts</td>
<td>Trash/shells</td>
<td>11.2</td>
<td>3.1 (5.98)</td>
<td>10-13.8</td>
<td>3-6</td>
<td>95-105</td>
</tr>
<tr>
<td>Sugar</td>
<td>Bagasse</td>
<td>15.4</td>
<td>4.3 (5.25)</td>
<td>12.2-14</td>
<td>2-4.5</td>
<td>155-170</td>
</tr>
<tr>
<td></td>
<td>Tops</td>
<td>15.8</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coffee</td>
<td>Husks</td>
<td>15.9</td>
<td>4.4 (4.61)</td>
<td>12.5-15</td>
<td>6-7.5</td>
<td>220-320</td>
</tr>
<tr>
<td>Wood</td>
<td>50% Moisture</td>
<td>9.5</td>
<td>2.66*</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20% Moisture</td>
<td>15.5</td>
<td>4.34</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sawdust</td>
<td>16.2</td>
<td>4.54</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pellets</td>
<td>16.8</td>
<td>4.70</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry non-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>resinous</td>
<td>19</td>
<td>5.32</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry resinous</td>
<td>22.5</td>
<td>6.3</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. Sources. LHV, Calorific Value: Okello et al., 2013; Moisture Content, Ash Content, Bulk Density: Okure et al., 2006; Wood figures Ashton, 2007.

Note. *KWh/kg for wood values calculated by multiplying MJ by .28 (1MJ = .28kWh)

The required biomass for a given project can be calculated by converting the total energy demand (KWh)/ year to total MJ demanded given the LHV (MJ/kg) of the biomass.

Required biomass amounts also give information regarding storage space required for a system, evaluated in section IV. Costs and Quality of Feedstock (CQ.2). A business model which incorporates briquetting into their operations may require additional biomass.
Finally, establishing the biomass demand requires establishing the overall efficiency of the bioenergy technology being used. Below are example calculations for a biomass gasification system.

**Table 3. Conversion efficiency assumptions for biomass gasification system**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency estimate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Combustion Engine</td>
<td>25</td>
</tr>
<tr>
<td>Generator</td>
<td>90-95</td>
</tr>
<tr>
<td>Whole system electricity generation</td>
<td>16.6*</td>
</tr>
<tr>
<td>Whole system with heat recovery</td>
<td>17-80</td>
</tr>
</tbody>
</table>

* Assumes 25% efficiency for IC Engine and 95% for generator
Source. Joerg, 2013

From these figures calculate total energy input and total biomass needed to meet energy requirements. An example calculation is below:

Energy demand: 6hrs at 10kw five days/week = 60kWh/day x 260 days = 15,600kWh/year

Biomass-energy statistics used for Maize Cobs: 1.2-1.5kg of biomass/kWh OR 3.5kWh/kg of biomass

Biomass requirement with Maize Cobs: 15,600kWh = 3.5kWh/kg (X)/(.116) = 27857kg/year or 27.86 metric tons/year

### 3.4 DETERMINE POTENTIAL BIOMASS SUPPLY OPTIONS

Because community contexts will vary widely, clearly defining the supply option and management scheme that is being assessed is an important first step in accurately considering and comparing costs and benefits. See Figure 1 for an outline of potential supply options and management schemes that can be considered through this framework:
3.4.1 PREAGGREGATED BIOMASS

Byproducts of business operations provide a potential available supply for bio-energy systems. These could include large quantities of agricultural residues near agro-processing centers or waste biomass from milling operations.

3.4.2 PURCHASE OF AGRICULTURAL RESIDUES FROM FARMER COOPERATIVES OR INDIVIDUAL FARMERS

Agricultural residues such as maize cobs, groundnut shells, and coffee husks can be processed and used effectively in the energy system technology. These could be accessed directly from individual farmers or through agreements with farmer cooperatives.
3.4.3 FIREWOOD

EXISTING WOODLOTS

Firewood can be bought directly from farmers who sell their excess firewood. There is a degree of certainty that the wood comes directly from their woodlots, and in buying this wood, money and value goes directly to the local farmers. However, deforestation leakage created through purchase of current sources of firewood or charcoal supplies is a concern.

OPEN MARKET

Firewood can also be purchased from those in the community or nearby villages which sell large quantities of firewood at market price. This adds a degree of uncertainty as to where this wood comes from and if the local firewood market adds directly to regional deforestation/degradation of natural forests.

3.4.4 AGROFORESTRY

Using agroforestry systems to supply biomass for the energy system has potentially many benefits in terms of environmental sustainability, benefits to farmers and the community, biomass quality and technology lifespan. As will be assessed through framework application, agroforestry has been found to have positive effects on incomes of marginalized populations, as well as lessen pressure on local forest reserves (Fabe et al., 2014). By incorporating trees into agricultural systems, woody biomass can be supplied to the bio-energy system while minimizing land competition for food production. Agroforestry systems could include a combination of intercropping, hedgerows, or growing trees on fallow land using nitrogen fixing tree species.

Because agroforestry involves developing complicated systems often requiring training and support, working with support organizations is
important to their success. Pamoja will work with local organizations such as Vi-Agroforestry that have a track record in working with farmers to implement agroforestry systems, providing seedlings, training, support and monitoring.

The management scheme and impact of woodlots is further defined by the biomass species chosen. This level of analysis required when implementing an agroforestry scheme requires a partnership with a qualified partner to ensure success with this supply option. For instance, species need to be evaluated on the following criteria:

- Coppicing ability in case of perennial applications
- Water efficiency
- Nitrogen fixing
- Non-invasive
- Harvesting process

### 3.4.5 NEW DEDICATED WOODLOTS

In starting small woodlots on farms, the species selected must be compatible with agriculture. Consideration of new woodlots will also need to clarify land-use change to minimize interference with land already being used for agriculture. Planting on land unsuitable for farming such as degraded land or hillsides could reduce competition with crop production. Land untenable for farming may be used as pasture.

#### OUTGROWER SCHEME

Pamoja could contract out the task of establishing and managing woodlots to local community members, then purchasing wood grown and harvested specifically for use in the bio-energy system. While farmer choice ultimately dictates land-use change for establishing woodlots, Pamoja wants to be aware of the impact outgrower strategies may or are having on social and environmental conditions. Most small-holder farms are maximizing land productivity, with little space going unused.
LEASING LAND

If leasing or buying of land is a common practice in the community, Pamoja can lease land for an extended time (around 5-10 years). In this case, Pamoja would manage the woodlot, internalizing costs and risks.

BUYING LAND

Purchase land and establish woodlots that are owned and managed internally. Securing land titles can be a major challenge for this option.

4 CRITERIA AND STANDARDS FOR A SUSTAINABLE BIOMASS SUPPLY

Four criteria (Figure 2) can be used to evaluate the biomass supply. Criteria and sub-criteria are listed below:

Figure 2. Sustainability Criteria and Sub-Criteria
Indicators within each sub-criteria can be measured to evaluate the performance of the supply. Decision support software is being developed to assist in the logistical organization and comparison of criteria performances.

I. RELIABILITY

R1. SUPPLIER RELIABILITY

Local farmer cooperatives, private and government landowners, business owners and market participants can be considered as potential suppliers. It is important to have a primary supplier of biomass, while also keeping backup options available. The following supplier criteria can be considered:

R1.1 SUPPLIER LEVEL OF ORGANIZATION: This can be assessed by looking at years in operation, group or individual productivity and production levels, finances, and satisfaction of customers or members. It is important to gather information from independent organizations.

R1.2 SUPPLIER NUMBERS: Sourcing from a large number of farmers avoids reliance on a single supplier, which can build resiliency. However, having one reliable point source for a supply can greatly reduce management costs of the supply chain. The organization of a cooperative helps to bring together the collective resources of farmers in a way which may ease management of a supply incorporating a large number of suppliers.

R1.3 SUPPLY CONTRACT: Willingness to enter into a contract guaranteeing a certain amount of biomass supply at a fair market price can also enhance the reliability of the supply.

R1.4 SUPPLY PROXIMITY: Biomass supply radius: The collection distance for the site. Eg. A site with poor road conditions or transportation may only be able to collect materials from a distance of 3km, whereas a site with access to a truck and/or better road conditions can collect materials from a larger radius. Collection ability for these projects range from a minimum of 3km to a maximum of 13km depending on transportation infrastructure.
R1 METHODS FOR CASE STUDY APPLICATION

R1.1.1 Years in Operation uses a scalar score from 1-20 years.

R1.1.2 Productivity is represented by kilograms of maize per year with a range of 30 to 200,000 kg/yr possible.

R1.1.3 Finances is scored on an ordinal scale from 1-10, 1 representing poor finances and 10 representing the best finances. For the case study scoring a business manager scored the sites along this scale.

R1.1.4 Member/customer satisfaction is scored on an ordinal scale from 1-10, 1 representing not satisfied and 10 representing very satisfied. For the case study scoring a business manager scored the sites along this scale. Future research could include a survey question for cooperative members and customers regarding their satisfaction with the supply entity.

R1.2 Supplier Numbers is scored on an ordinal scale from 1-10, 1 representing a poor fit for supply numbers and 10 representing a good number of suppliers. An ordinal scale was selected for this indicator because fewer or more suppliers may be appropriate depending on the system context. For the case study scoring a business manager scored the sites along the ordinal scale.

R1.3 Contract carries a score of 10 for yes a contract is signed to .01 for no contract signed. Interview responses with business managers were used to score the indicator.

R1.4 Supplier Proximity was scored on a scalar range of 3km to 13km. A larger range represents higher reliability and so a better overall score.

R2. SUPPLY DYNAMICS

We will consider the recent and projected dynamics of the potential supply in the area; ideally choosing a market with a large and relatively stable supply of biomass.

R2.1. SEASONALITY/VARIABILITY OF SUPPLY AVAILABILITY

Agricultural residues

- Types of crops and crop seasons: In order to design the biomass supply chain, we need to know the type of crops grown in the village whose residues can be used in the energy system, as well as their harvest seasons. Crop productivities between the two seasons will also be considered.
- Area cultivated for each type of crop and any major fluctuations past 5 years
* Local land productivity (dry-tons/ha/season) past 5 years
* Diseases, crop fluctuations, or natural disasters in the last 5 years

**Pre-aggregated biomass**
* Types, amounts of incoming biomass, seasonal fluctuations and any fluctuations over last 5 years.
* Residues created per amount of primary biomass.
* Technological history last 5 years (breakdowns etc. that would interrupt the flow of biomass through the aggregation point)

**Woody biomass**
* Area of planted trees/species
* Coppice cycle for each tree species
* Total wood harvested (dry-tons/ha/season)
* Harvest times, staggering of plantings

**R2.2 STORAGE CAPACITY**
Storage capacity is an important consideration in supply dynamics. Some technologies such as gasification systems require a feedstock with maximum moisture content of 15-20%. Without proper storage, variable influxes of biomass can result in major amounts of unusable feedstock, which cannot be counted in the available supply. Therefore, when weather has the potential to render feedstocks unusable, available supply cannot exceed the available storage space.

**R2 METHODS FOR CASE STUDY**

R2.1.1 number of harvest seasons/year uses a scalar score of 1-4 harvests per year. 1 harvest season represents a poor score and less reliable supply.

R2.1.2 Shock Impacts Last 5 Years is scored as a percentage of crops reported effected by shocks including drought, pests, or weather events in the past five years. Data was gathered through survey data.

R2.1.3 Crop Productivity Trends is scored using an ordinal scale from 1-10 and was scored by the business manager.

R2.2 Storage Capacity Ratio is a percentage estimate of site storage capacity against needed supply volume. Scores were calculated from interview responses and system calculations provided by Pamoja.
R3. COMPETING DEMAND DYNAMICS

In implementing a sustainable biomass supply, Pamoja must consider the dynamics of demand in markets that compete with the potential biomass supply. Different aspects are taken into account:

R3.1 LOCAL POPULATION DYNAMICS: An increase in population will naturally lead to an increase in demand for wood and/or other demands on the supply option. For example, it may be important to know the rate of the population using agriculture residues for cooking as this demand has an impact on availability.

R3.2 COMPETING USE BUSINESS TRENDS: Are there other businesses creating a competing market for the biomass supply? At what quantities and prices and how have these changed in the past 5 years? Eg. What are wood prices for other markets competing with fuelwood (wood for construction, charcoal), eg. Use of agricultural residues by chicken farmers for bedding. Investigate alternative uses and markets for the biomass in question.

R3.3 COMMUNITY BEHAVIORAL DYNAMICS: Studies indicate access to electricity can significantly change demands and behaviors in a community (Madubansi & Shackleton, 2006). These trends can be used to predict possible shifts in demand for competing uses. Investigation into community behavioral trends in response to electricity access can inform predictions of possible behavior change impacting supply reliability.

R3 COMPETING DEMAND DYNAMICS CASE STUDY METHODS

R3.1.1 Population Growth Rate has a best-worst scale of 0-5%. National level data was used for the study score.

R3.1.2 Percentage of Supply Being Used by Population represents supply amounts being used for personal or other uses by people within the community. The figure is a percentage score from 0.01-100. Data is sourced from survey responses.
R3.1.3 Population Percentage Using Supply indicates the percentage of respondents reporting “other” uses for the biomass supply. Survey responses are used to generate a score from .01-100%.

R3.2.1 Market Price Changes is uses data from the 2015 Ugandan Consumer Price Index to calculate percentage increases or decreases in prices over the last four years.

II. SOCIAL/ECONOMIC IMPACTS

Bioenergy systems have a unique opportunity to create additional economic activity and social benefits in a community not only through the generation of electricity and valuable byproducts, but also through the establishment of the biomass supply chain.

The incorporation of, and symbiotic relationship between energy generation, natural resources, and human stewardship is an important element which sets bioenergy systems apart from other renewable energy options.

SE1. VALUE CREATION AND DISTRIBUTION

The sustainability criteria also measure value creation through social capital development for the local community. Creating income generation and new skills at the local communities is a crucial aspect for the overall sustainability of the biomass supply chain.

SE1.1 INCOME GENERATION

In order to assess the total income from biomass production the following inputs are required to calculate the total impact.

- Number of farmers participating in biomass supply chain (Category 1: 1-3 acres, Category 2: >3-5 acres, Category 3: above 5 acres)
- Net earnings per farmer ($/ha/year/farmer)
- Supply levels by farmers (Reported from existing system monitoring)
- Use gestation period to grow the biomass and demand characteristics of bioenergy system to calculate biomass supply provided/season and or/year
- Total amount of supply available from farmers (dry tons)
- Multiply price of biomass (what Pamoja will pay for supply) by total supply needed to calculate total additional income from biomass supply.
• Other local income from biomass supply chain: Income through transportation, pre-processing, storage maintenance, etc.

SE1.2 INCOME DISTRIBUTION

Income distribution is important for accurately understanding the social impact of the community as income generation can mask pooling of wealth, increased inequality, and further marginalization of poor community members. To calculate the income distribution of a system gather the following information:

• Total additional income divided by number of suppliers to get at portion of population impacted
  o Compare current income to income per amount of product and demographics of suppliers to find %income increase numbers
• Variation of income generated: How does additional income from the biomass supply chain affect current relative distribution of wealth? What are the percentage changes of income and where is additional income being distributed?

SE1.3 SOCIAL CAPITAL

Social capital can be measured and accounted for by determining the social impact through local capacity building.

Employment Environment and Supply Impact

To measure social capital the framework can measure the number of jobs created by the supply chain. New employment opportunities connected to the supply chain could include growing/supplying biomass, transportation, and processing.

Calculate the number of and types of jobs created through the biomass supply chain.

Skill Environment and Supply Impact

Survey data and business models can provide information on skill development resulting from the biomass supply chain. Content area and capacity development could include forestry and agroforestry knowledge
and skills, agricultural management training, as well as increased cooperative organizational capacity.

In order to assess the impact of capacity building, the following information needs to be provided:

- Number of trainings conducted
- Number of local people trained
- Number of trainees getting a job within three months after training
- Average income of trainee who got placed

### SE1 CASE STUDY METHODS

SE1.1.1 Percentage of Farmers Participating represents the percentage of survey respondents reporting they have supplied the biomass system.

SE1.1.2 Net earnings/farmer is scored by calculating the total amount of biomass supplied multiplied by the price/kg and then divided by the total number of farmers participating. Because not all data was available for this calculation Pamoja estimates were used. The earning are reported in UGX/year.

SE1.1.3 Other Income is calculated through calculating the wages of those indirectly or directly employed by Pamoja and dividing total wages by the number of employees. This number was also estimated by Pamoja staff for the case study.

SE1.2.1 Standard Deviation of Supply Amounts calculates the standard deviation of reported supplies to indicate the level of variation in supply amount. This allows evaluation of income distribution otherwise masked by averages.

SE1.3.1 Job Creation and Type is scored using a rubric available in the SE scoring Tab of the Indicator Scoring Worksheet available on the Pamoja website. The number and skill level of jobs created sum to a score between 1 and 100 with 1 being a low score and 100 being a high score.

SE1.3.2 Number of Trainings Conducted relates the number of trainings reported by Pamoja and Partner Organizations.

SE1.3.3 Number of Attendees at Trainings is the total number of attendees at trainings gathered through Pamoja and Partner reporting as well as from survey responses.

### SE2. RESOURCE COMPETITION

#### SE 2.1 LAND-USE COMPETITION
There is a risk for potential land use competition between biomass production and food production when establishing woodlots or introducing agroforestry practices. In contrast, using agricultural residues are not associated with a risk for land use competition. Rather, residue use causes environmental impacts including leakage from cooking and fertilizer addressed below (E1; E2).

### WOODLOTS

The use of degraded lands may be used for biomass production if the land is unsuitable for food crop production. Degraded lands are sites which are too hilly, too rocky or with little soil depth making it unsuitable for food crop production. New woodlots should be developed on marginal lands not suitable for food crop production.

Creation of woodlots may also eliminate community or private grazing land. Establishing a baseline figure for grazing lands in the project site area and monitoring changes in size of grazing spaces through surveying can provide information about the impact of woodlots on grazing land.

### AGROFORESTRY

In order to avoid the food vs. fuel debate the following land-use management schemes can be considered for promotion of biomass plantations:

- Monitor changes in cropping patterns
- Crop productivity vs reliability: Agroforestry systems have been shown to increase the stability and reliability of harvests (Thorlakson, 2012; Leaky, 2010, Kristjanson, P. et al., 2012). Future crop productivity estimates (harvested tons/ha/season) will be compared with the harvest of the previous years (before agroforestry model). The percent reduction of productivity needs to be considered, along with the trends in reliability of crop production associated with agroforestry systems.
- Avoid displacement of food crops for biomass production
- Boundary plantations/Hedge rows: The use of farm boundaries for biomass plantations. This may have a lower impact on space planted for food crops which could be offset by positive impacts on soil quality, and run-off prevention depending on the species planted (Lenka et al., 2012).
o Can have positive impacts on income returns, which are in some instances offset by high opportunity costs of adoption (Pattanayak, 1997).

- Intercropping: Can positively impact soil conditions but may also reduce overall yields depending on the intercropping species and works especially well with shade plants like coffee or yerba mate (Ilany et al., 2010).

SE2.2 COMPETING USES FOR BIOMASS

The sustainability criteria can also measure the impact of the use of a particular biomass and its effects on other competing uses. Is the biomass being used by others? In what amounts and when? Specific categories of competing use are:

- Fertilizer
- Cooking
- Fodder for animals
- Business uses: Bedding at chicken farms, fuel for kiln
- Etc.

BIOMASS REQUIREMENT

Total biomass required to produce electricity should be compared to supply available after accounting for competing uses. The biomass requirement is calculated by finding the required biomass to produce estimated or actual electricity demand as well as the total biomass available in the community. By calculating this number as a percentage of total biomass available in local area, as well as calculating estimates of percentage of biomass used for competing purposes, decision-makers can be informed about potential resource competition thresholds in each context.

Data can be gathered and analyzed about current biomass use trends as data is available, possibly as a percentage of available biomass Eg. What is the percentage of available biomass used for cooking or fertilizer?

SE2. CASE STUDY METHODS

SE2.1.1 High/Low Risk of Landuse Competition Leakage is scored using an ordinal scale between 1 and 10. 1 represents a low leakage risk and 10 represents a high leakage risk.

SE2.1.2 High/Low Fertile Land Competition Risk Leakage is scored using an ordinal scale between 1 and 10. 1 represents a low competition risk and 10 represents a high competition risk
SE2.1.3 Change in Landuse indicates the percentage of land converted from forest to agricultural land due to biomass demand. Survey data was used for calculations.

SE2.2.1 Percentage of Total Supply Used for Personal Use is calculated from survey responses.

SE2.2.2 Competing Demand is an ordinal score 1-10, 1 representing low competing demand and 10 representing high competing demand. For this case study Competing Demand was scored by a project manager.

III. ENVIRONMENTAL IMPACTS

E1. DEFORESTATION AND DEGRADATION OF FORESTS

Deforestation and degradation of natural forests are currently the most serious concerns when implementing a bioenergy system and supply chain. It is crucial that the fuel-wood supply does not contribute to the deforestation/degradation problems already facing Uganda. The current forest cover of the project area, recent changes, and deforestation issues will be noted.

Supply chains can be assessed to determine if the production of the biomass is alleviating pressure on local managed or natural forests and local tree cover; or, due to leakage, contributing to deforestation. The boundary of the project will be defined as a community boundary. However, leakage concerns need to also be addressed.

By-products (biochar): If there are any by-products which are getting produced that are mitigating the pressure on deforestation this can be quantified by determining how much of such byproducts are generated and what amounts of wood/charcoal products are being replaced.

Reforestation: the establishment of woodlots on degraded land may contribute positively to forest cover when species biodiversity and proper management is observed. Therefore, in the case of establishing woodlots, Pamoja assumes no risk of contributing further to deforestation/degradation.
Scoring the supply chain on the level of certainty with which you can determine the source of the supply and its direct contribution level to deforestation (e.g., open wood market purchases) can also allow consideration of deforestation/forest degradation issues.

**E1 CASE STUDY METHODS**

E1.1 Land-use Change Risk is measured on an ordinal scale from 1-10, 1 representing low land-use change risk and 10 representing high risk. For the case study, a pamoja manager assessed the land-use change risk. For future assessment, a more accurate analysis by a qualified expert is recommended.

E1.2 Trees Planted represents the number of trees reported planted through survey responses as well as through partner records. For the case study, scoring partner reports were used although they are not corroborated by survey responses.

E1.3 Mitigation Byproducts is scaled as a yes/no variable with a score of 10 for a yes response that the supply supports byproducts that mitigate deforestation pressures. A no answer scores .01 for this indicator. The project manager scored the case study sites.

E1.4 Leakage Score represents a high to low risk for leakage, or deforestation pressure occurring beyond the boundary of the assessment due to supply chain management. The score is an ordinal scale from 1-10 with 1 representing low leakage risk and 10 representing high risk of leakage.

E1.5 Supply Source Certainty represents the level of knowledge surrounding the supply source held by the energy company. It is scored on an ordinal scale of 10-1 with 10 representing high level of certainty regarding the supply sources and 1 representing a low level of certainty around the supply source.

**E2. SOIL QUALITY**

Efforts will be taken to maintain soil quality in fertile lands and restore soil quality on non-arable or degraded land. Growing suitable trees on degraded lands and hillsides has documented potential to conserve soil, reduce soil runoff, and add nutrients and organic matter to the soil, through N-fixing trees and mulching leaves and branches. Agroforestry has more favorable effects on soil fertility and other soil properties (Shoga'a Aldeen, 2013; Pandey et al., 2000; Thevathasan et al., 2014).

Does the proposed supply chain cause environmental impacts regarding soil quality and in what way?
E2.1 NUTRIENT CYCLE

Nutrient content of soil within agricultural systems is critical to productivity across all time scales. The biomass supply chain has the potential to contribute to the soil nutrient balance or negatively impact soil nutrients through significant nutrient removal. Agroforestry systems have been shown to improve soil quality. (Shoga’a Aldeen, 2013, David & Raussen, 2003).

To evaluate if a biomass supply is positively impacting soil nutrient content, review the following criteria:

- **Change in nutrient availability:** What amount of nutrients are being removed or added (ash/biochar) from the agricultural system due to biomass supply?
- **Agroforestry and woodlot impacts:**
  - What is the total acreage and/or number of trees planted on degraded/fallow land planted?
  - What is the increase in plant-available soil nutrients (Nitrogen fixing trees)?
  - What is the total acreage of intercropping for soil improvements?
  - Are leaves staying on ground?

Because most of the corn residue remains following a cob and grain harvest, and because the nutrient removal is relatively low from cob harvest (approximately 5 lb N/a), the impact of cob harvest on soil erosion or soil organic matter levels is likely to be low. Also, because the nutrients removed in a cob harvest of 1,200 pounds per acre was estimated to be 4 lb N/a, 1.3 lb P2O5, and 7 lb of K2O, the value of the nutrients removed in the cobs will also be relatively low (Roth & Gufstovson, 2014).

E2.2 SOIL STRUCTURE

Soil structure impacts the movement of air and water within the soil, as well as biological activity, root growth, and seed behavior. Improvements to soil structure can contribute to sustained agricultural productivity. To evaluate the biomass supply impact on soil structure the following criteria can be investigated:
• **Trees increase water holding capacity, and improve soil structure:** Does the biomass supply chain improve water management through planting of trees?

• **Annual crops to perennial crops and no till agriculture:** Does the biomass supply result in a shift to perennial crops or no till agriculture which is less disturbing of soil?

• **Erosion control:** Does the introduced biomass supply chain result in a decrease of erosion by providing cover for fallow land and a permanent buildup of soil depth? What is the total acreage of erosion control measures implemented?

• **Crop rotation:** if agricultural residues are used, is the practice of crop rotation kept at current levels or increased to contribute to soil health?

• **Impact on organic matter:** Does the introduced biomass supply chain result in an increase in organic matter in the soils contributing to increased water holding capacity and nutrient availability? Does the supply remove organic matter?
  - This can be measured by identifying the number of farmers using residues for fertilizer, and estimated amount used each season, and calculations regarding its contribution to nutrient levels.
  - Calculation of removal of nutrient content of biomass can provide further details on nutrient removal impact for biomass supply. For example, maize cobs have been found to contribute only a small percentage of nutrient total for maize residues. See Table 5:

<table>
<thead>
<tr>
<th>Component</th>
<th>Dry Matter (% Total)</th>
<th>Nitrogen (%N)</th>
<th>Phosphorus (%P205)</th>
<th>Potassium (%K20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grains</td>
<td>48</td>
<td>1.44</td>
<td>.69</td>
<td>.5</td>
</tr>
<tr>
<td>Stalks</td>
<td>22</td>
<td>.43</td>
<td>.14</td>
<td>.9</td>
</tr>
<tr>
<td>Leaves</td>
<td>10.6</td>
<td>1.8</td>
<td>.69</td>
<td>2.05</td>
</tr>
<tr>
<td>Sheaths</td>
<td>5.3</td>
<td>.64</td>
<td>.37</td>
<td>1.74</td>
</tr>
<tr>
<td>Husks</td>
<td>4.3</td>
<td>.36</td>
<td>.21</td>
<td>1.32</td>
</tr>
<tr>
<td>Shanks</td>
<td>1.5</td>
<td>.5</td>
<td>.18</td>
<td>1.68</td>
</tr>
<tr>
<td>Cobs</td>
<td>7.5</td>
<td>.33</td>
<td>.11</td>
<td>.62</td>
</tr>
<tr>
<td>Tassels</td>
<td>.5</td>
<td>.97</td>
<td>.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Lower ears</td>
<td>.5</td>
<td>2.04</td>
<td>.87</td>
<td>3</td>
</tr>
<tr>
<td>Silks</td>
<td>.2</td>
<td>3.5</td>
<td>.87</td>
<td>2.57</td>
</tr>
</tbody>
</table>

*Source. Iowa State University, 2007*
E2. CASE STUDY METHODS

E2.1.1 Change in Fertilizer Availability is scored against an ordinal scale of 1-10 by a pamoja project manager. It represents a qualitative estimate regarding nutrient removal or addition due to the supply chain in a community. Future scoring would be more accurate if conducted by an independent environmental consultant.

E2.1.2 Number of Trees is a proxy for nitrogen fixing in the soil. Numbers are reported from survey responses and project partners.

E2.1.3 Degraded Land Restoration is an ordinal scale from 1-10 and was scored by a Pamoja project manager.

E2.2.1 Change in organic matter is an ordinal score based off a scale 1-10 10 representing positive changes to organic content, 5 representing neutrality and 1 representing removal of organic content. Scores were calculated using survey responses and calculations regarding cob nutrient content from Joerg 2013.

E2.2.2 Tree Coverage is an ordinal scale from 1-10, 1 representing conversion to agriculture, 10 representing new forest coverage. Survey responses regarding planting number and location of trees was used to score sites and supplies.

E2.2.3 Perennial Crops of No Till Agriculture represents a yes/no variable with 10 equalling a yes answer and 1 equalling a no response. Survey responses were used to score the variable.

E3. WATER TABLE

The water efficiency of the biomass species can be evaluated using the following data:

- Water requirement for the biomass
- Rain water harvesting technologies used
- Total acreage planted for water conservation- Are agroforestry systems being used which utilize trees to retain water in soils and fields through hedgerows or intercropping?

E3. CASE STUDY METHODS

E3.1 Water Requirements of Supply was calculated from annual rainfall averages required for supply species as listed in FAO and the Agroforestory Database (citations available via Indicator Scoring Worksheet in User Toolkit).
E3.2 Rainwater Harvesting Technology Used represents a scale from 1-10 with 1 being no technology used and 10 being frequent technology reported. Survey responses, observation and partner reports were used to score this indicator.

E3.3 Degraded Land Restoration is scored as a yes/no variable with 1 representing no and 10 representing yes. Survey responses and partner records were used to score this indicator.

### E4. BIODIVERSITY

The biomass supply chain should further enhance rather than diminish the local biodiversity. Risks towards local biodiversity can be minimized through providing a diverse landscape incorporating elements such as hedgerows or intercropping with trees (agroforestry) or preference of indigenous over non-native biomass species.

Indigenous/Native Species: The use of indigenous and native species should be given preference. There must be at least one biomass species and 25% of the total biomass from native species.

### E4. CASE STUDY METHODS

E4.1 Use of Native Species is scored as a yes/no variable with 1 representing no and 10 representing yes. Manager interviews, Partner records, consultant interviews and observation were used to score the indicator for the case study sites.

E4.2 Intercropping and Hedgerows were scored on an ordinal scale from 1-10 with 1 representing high use of Intercropping and Hedgerows and 1 representing no use. Survey responses and observation was used for this indicator scoring.

### E5. SUSTAINABLE FARMING PRACTICES

In cases where the establishment of the supply chain contributes to or enables sustainable farming practices including the use of agroforestry, positive environmental impacts are assumed. Providing a qualitative score for the supply chain's encouragement of sustainable practices allows broad assessment of the integration of sustainable concepts.
Does the energy system supply chain encourage the use of sustainable agricultural and silvicultural practices in growing trees?

Does the system encourage the use of natural fertilizer?

Does it encourage the use of other sustainable and beneficial systems such as agroforestry systems, crop rotations and fallows, among others?

Does it provide for or facilitate training, discussion, and skill development around sustainable farming practices?

E5. CASE STUDY METHODS

E5.1 Number of Trainings uses survey responses, Pamoja records, and partner records to report the number of trainings regarding sustainable farming practices on a scale from 0 to 20 trainings.

E5.2 Number of Attendees uses the same data sources to calculate the number of attendees to the trainings.

E5.3 Number of SF Practices uses survey responses to score the number of sustainable farming practices being reported by survey respondents.

E5.4 Percentage of People aware of SFP uses survey responses to calculate the percentage of respondents who report and awareness of SFP.

E.6 CARBON CYCLE

Carbon emissions from bioenergy systems are driven in the first case by the net carbon fluxes to the atmosphere from the ecosystems where the biomass is sourced from rather than the fossil fuel emissions from e.g. processing biomass or producing the conversion technology (Buchholz et al. 2015).

Additionally, various changes in land use and/or land management practices can be used for potential SOC sequestration in different regions, including reducing tillage intensity and frequency or conversion to no-till agriculture, reducing bare fallow, conversion of highly
erodible land to grassland or woodlots, increased use of cover crops in annual cropping systems, and natural woodland regeneration (Lal, 2009; Lorenz et al., 2014; (Paustian et al., 1997; Hutchinson et al., 2007) Woodland plantations have been found to mitigate atmospheric carbon levels over the long term (Van Minnen et al. 2008).

Carbon impacts from the bioenergy system will be assumed at least neutral as long as the system is not contributing to deforestation (Zanchi et al., 2013). Assuming carbon neutrality must include an assessment of competing uses potentially contributing to leakage. Examining the data gathered in the resource competition section (SE2) can help determine if leakage contributing to deforestation issues is a concern for the biomass supply.

- What are the competing uses of the biomass in question?
- At what levels is the supply being used for these purposes and what percentage of available biomass is being used?
- Are these uses mitigating use of forest products and does the establishment of the supply chain contribute to increased reliance on forest products?

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### E6. CASE STUDY METHODS

E6 Carbon cycle is assumed to be neutral if not contributing to leakage. This is rated on an ordinal scale from 1-10, 1 being neutral and 10 being severe carbon emissions.

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### IV. SUPPLY COSTS/QUALITY

#### CQ.1 COSTS OF SUPPLY

Cost of biomass contributes significantly to the economic viability of bioenergy systems. While including reliability, social, and environmental considerations into management decisions, Pamoja’s goal is to choose a supply which creates a financially sustainable final cost of biomass, including costs associated with processing and transportation. Quality considerations are also important to project sustainability as the quality of feedstock can have major implications for technology life span and maintenance costs. Aspects Pamoja will consider in final biomass cost include fixed and variable costs listed below:
Wood biomass options have high variability in moisture content and in density amounts for storage dependent on processing methods which should be considered in cost analysis.

**CQ1. CASE STUDY METHODS**

(See CQ scoring tab in Indicator Scoring Worksheet in User Guide Appendix D for CQ calculations and sources)

Scores gathered from Pamoja Manager Interviews and Estimates

CQ1.1 Storage Costs- Scored as ugx/m³

CQ1.2 Capitol Costs of start-up is scored by USD

CQ1.3 Market Prices scored by prices for supply in UGX

CQ1.4 Processing Costs calculated in ugx/kg

CQ1.5 Transportation Costs calculated as UGX/kg

CQ1.6 Training Costs as reported by Pamoja and Partner staff

CQ1.7 Maintenance and Management as reported by Pamoja management in $/kWh

CQ1.8 Whole System Costs is represented by the Levelized Cost of Electricity

**CQ2 QUALITY OF FEEDSTOCK**

The quality of the feedstock being used can have important impacts on the lifespan and maintenance requirements of the bioenergy technology. In gasification systems specifically

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**Table 6. Fixed and Variable Project Costs**

<table>
<thead>
<tr>
<th>Fixed Costs</th>
<th>Variable Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage space</td>
<td>Market prices</td>
</tr>
<tr>
<td>Training</td>
<td>Processing</td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
</tr>
<tr>
<td></td>
<td>System management, monitoring, assessment</td>
</tr>
</tbody>
</table>
this also effects the quality and energy content of the gas. Poor feedstock can lead to significant difficulties with the technology due to ash creation, as well as tar and silicate presence that build up in the engine.

Biomass options will be evaluated against the following quality metrics:

- Moisture content
- Ash content (also as a proxy for acidity)
- Handling features (e.g. flow characteristics) and processing requirements
- Bulk density and energy density

### CQ2. CASE STUDY METHODS

CQ2.1 Moisture Content is a scalar score based on data from Joerg 2013

CQ2.2 Processing Requirements is scored on an ordinal scale from high (10) to low (1) requirements using All Power Lab factsheets and Information from Christensen, 2012.

CQ2.3 Energy Density is scored as kWh/kg using data sources within this Framework.

CQ2.4 Ash content is scored as a percentage score based off data from the Center for Transportation Analysis (sources available in Indicator Scoring Worksheet within User Guide and Toolkit).

### 5. CRITERIA WEIGHTING

Weighting of the criteria establishes comparative importance levels between criteria under consideration. Decision makers can make decisions regarding weights of criteria, can investigate how varying weights impact management decisions, and can make weighting decisions regarding thresholds (yes/no scenarios that could lead to immediate rejection of a potential site or project). Literature reviewing multi-criteria analysis and bioenergy project planning can provide guidance regarding appropriate decision structuring for applying this framework (Scott et al., 2012; Buchholz et al., 2009).

### 6. DECISION MAKING PROCESS
A simple multi-criteria utility decision support tool is being developed in conjunction with this framework using Analytica decision support software (Decision Analytics, 2015). This tool and a guide to its use will be available via the Pamoja website and provides one application method for the framework. The decision tool and guide provides instruction and guidance on implementation including suggestions for criteria weighting, data collection, indicator measurement techniques, and building a decision process. Reviewing literature regarding decision support processes and programs for bioenergy systems can also provide further guidance in determining a decision structure for framework application (Scott et al., 2012; Buchholz et al., 2009, Kurka & Blackwood, 2013).

Based off the weighting of criteria, goals and priorities of the company, a decision can be made which clearly defines and takes into account the many elements necessary to secure a sustainable biomass supply. Combination assessments and short vs long term supply chain options can be developed with company explanation of scoring, clear biomass option descriptions and timescales being considered.
Chapter 5  SA User Guide and Toolkit

Introduction

This manual acts as guide for conducting a biomass supply sustainability assessment using the Assessment Framework for Biomass Supply Chain. The manual provides:

1. Step by step process guide for implementing a sustainability assessment for biomass supply chains including use of the Assessment Framework.
2. Definitions, clarification and guidance on criteria and indicators
3. Measurement tool instruction and techniques

The process guide has been developed with reference to current sustainability assessment literature from the emerging bio-energy field and more established forest management schemes (Chistensen, 2012) as well as existing policy evaluation tools.

Explicitly clarify assessment goal and definition of sustainable- sustainability assessments have a wide range of specific goals, definitions, accompanying criteria and indicators, this is generally acceptable and necessary but in result requires careful explanation of intentions and starting assumptions to allow evaluation and comparison within the “sustainable development” field. (Hacking & Guthrie, 2008 pg 82)
Step 1: Define Boundaries

The first step in developing a biomass supply assessment is to define the boundaries of your assessment. This involves determining what the scale of the assessment will be. A boundary defines what will be considered in the scope of the assessment and what will not. This framework is designed and best suited for project level analysis and community boundaries, however it can be tailored to fit the context of the user, who needs to set the geographic and temporal boundaries best suited to their purpose.

1.1 Setting a geographic boundary
The geographic scope determines the spatial scale at which indicators will be measured. Assessments can range from community level in scale, to regional, national or even global depending on the focus of the study. For example an assessor may decide to set a geographical boundary of the village level for a small project which does not extend its need for biomass supply beyond one village. Another assessment may wish to set a county level boundary to determine supply sustainability for a number of project sites in one larger area.

1.2 Setting a temporal boundary
It is also important to establish the time-scale at which the assessment will be measuring indicators. Sustainability assessments at this scale most often use a life cycle assessment process, assessing options in regard to the life expectancy of the technology, which for small gasifier systems is between 5-10 years.

Step 2: Mapping Receiving Environment

Understanding the social-ecological context of project sites is critical to developing accurate assessments of proposed or operating BGE systems. The outcome of this step should be a comprehensive description or “map” of the project environment including the characteristics and relationships of social, ecological, and economic
components. Details which may be included in a site environment map could include:

- Current state of the environment (social, ecological, economic status of the area and links between them)
- Legal and institutional background of the local area, region
- Drivers if change in the social ecological system (i.e., Development programs, policies impacting the area)
- Trend in changes in social ecological system
- Future development scenarios and/or actual plans

A receiving environment map may be compiled as a report, include pictures, narrative, and/or spatial mapping.

**Step 3: Determine the Energy Demand and Biomass Requirement**

The next step in assessing the sustainability of a potential feedstock is determining the total quantity of biomass that will be needed to meet the demand for the system, project, or community.

3.1 Calculate energy demand

This can be done through investigating the existing and potential energy markets through a calculation of current energy use in the area, population dynamics, community needs assessment, etc. Develop an understanding of the kinds of energy used in the community, for what purposes, in what quantities and at what costs; Cooking, agricultural processing, lighting, entertainment, etc. This assessment should take into account variability in load demands, both throughout the day and throughout the year. Ability to pay is also an important factor in assessing the potential demand of an area.

When operational

When investigating a site/area that is operational, using the system capacities will accurately establish a maximum energy demand, while energy
production records and supporting assessments and reports can provide detail on actual energy demand in the area over the course of operations.

When planned

When assessing the supply for a system that is in planning stage the planned system capacities can be used as a starting point, however gathering information on crop production and processing amounts, and/or entrepreneurial activities requiring power in the area could uncover important discrepancies between energy demand and planned system(s) capacity. Collaborating with partners who may have access to feasibility studies including data on potential energy demand is important to efficiently gather information at the planned project site.

When investigating

Energy demand calculation for a site in the initial stages of investigation is more involved and centrally important to determining the feasibility of system success and appropriate system capacity. Here again information should be gathered on crop production and processing amounts, and/or entrepreneurial activities requiring power in the area as well as demand and ability to pay for household level electricity. Collaborating with partners who may have access to feasibility studies including information on potential energy demand through existing data, surveys, or other tools can ease the data collection process.

Other considerations in calculating energy demand

It may be valuable to consider the temporal scale in calculation of energy demand. Increased access to reliable electricity has been shown (need citation) to cause an increased energy demand. When conducting an assessment at a system level, demand can easily be calculated using the system parameters. If conducting a community or regional level assessment, more time should be spent fully understanding the causes and potential energy demand of the area over the lifecycle of the assessment to accurately establish the necessary supply amount. This can provide valuable data regarding appropriate number and size of systems for projects still in development.

Costs of energy should also be accounted for in determining energy demand. Willingness to Pay or the ability to pay for the generated electricity including set up costs will impact the demand for project power. Considering the current access to
and cost of energy sources in relation to a proposed system is important in accurately estimating what the demand will be in an area.

3.2 Determine Required Biomass

Biomass required for energy generation

Energy demand can then be used to calculate the required amount of biomass to meet the energy needs of the community in question. (Cite existing literature and tools for conversion of energy demand to biomass needed)

Biomass required for additional activities

This assessment should also accurately reflect the management scheme or business model being used for the system. A business model which incorporates briquetting into their operations may require additional biomass. (existing literature on biomass to briquettes?, other references?) Refer to the example assessment for more information on calculating biomass demand for briquetting activities.

**Step 4: Establish Supply Options**

Select possible feed stocks considering the available options in the area. At this point it is important to communicate with stakeholders about their interests, preferences, and opinions regarding potential supplies. Assessment

Table 1. Biomass Supply Options

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preaggregated Biomass</td>
<td>Agricultural Residues</td>
<td>Firewood Market</td>
<td>Agroforestry</td>
<td>New Dedicated Woodlots</td>
</tr>
</tbody>
</table>
Step 5: Conducting the Assessment

5.1 Gathering Data

The appendices contain the survey tool and interview guides used to gather data for the assessment framework. Working off the toolkit example you can adapt the questions to best address the indicators of interest for your supply assessment. The data input table (Appendix C) lists the indicator data points, example sources, and scales used for scoring. Adapt this excel to your project specifications and use it to input and keep track of data points.

Step 6: Organizing data

Appendix D includes data organization and scoring tool. If the survey tool is adjusted, this input tool must also be adjusted in excel to incorporate new questions. Data from interviews relevant to scoring is included in the scoring tabs for each indicator being addressed, and those implementing this assessment may or may not choose to track their data this way.
The data input and scoring table (appendix...) Lists the indicator data points, example sources, and scales used for scoring. Adapt this excel to your projects specifications and use it to input and keep track of data points. Scoring tabs for each criteria are available to provide examples of indicator scoring techniques. These can be useful for tracking and justifying final scores.

Model use

Scores and weights are recorded within excel as well as saved in separate model versions to allow for easier scenario comparisons. The user interface allows entry by stakeholders or assessors into the model and display of results. The case study methods section of the Assessment Framework explains model inputs. The user interface displays detailed results for each indicator, subcriteria and criteria. Some manipulation of the results will be needed to communicate them effectively. See the results section of Chapter three of Perruccio Thesis- Using Multi Criteria Decision Analysis to Develop Sustainability Assessment Tools: Biomass Supply Chains for examples of results presentation.

**Step 7: Communicating results**

Keeping data points, scores and final results in excel form allows generation of graphs and visualizations to communicate results. Chapter three of Perruccio Thesis- Using Multi Criteria Decision Analysis to Develop Sustainability Assessment Tools: Biomass Supply Chains provides examples of data visualization strategies which may be useful to display assessment conclusions.

**User Guide Appendices**

A. Survey tool

**Questionnaire to the Community Monitoring Assessment 2014**

(Adapated from Joerg 2012)
1. Background information

<table>
<thead>
<tr>
<th>Name of interviewee:</th>
<th>Male/Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td></td>
</tr>
<tr>
<td>Contact Information:</td>
<td></td>
</tr>
<tr>
<td>Mobile:</td>
<td>Address:</td>
</tr>
<tr>
<td>Site Location:</td>
<td></td>
</tr>
<tr>
<td>District:</td>
<td>Parish:</td>
</tr>
<tr>
<td>Village:</td>
<td></td>
</tr>
<tr>
<td>How many people are living in your household? Total:</td>
<td>Adults:</td>
</tr>
<tr>
<td>How many are farmers:</td>
<td></td>
</tr>
<tr>
<td>Is the population of your village growing? Y/N</td>
<td></td>
</tr>
<tr>
<td>Are you part of a local farmers group? Y/N</td>
<td></td>
</tr>
<tr>
<td>Name of group:</td>
<td></td>
</tr>
<tr>
<td>Position in the group:</td>
<td></td>
</tr>
</tbody>
</table>

2. Agricultural Residues

| What is the size of your land? |             |
| What are the major crops grown? How much area do you use for each crop? |             |
| Does crop distribution change year to year? How? Has what you’ve grown changed in the last five years? |             |
Were there any natural disasters in the last 5 years affecting your harvest (insects, drought, irregular weather, fire etc)?

What crops were affected? What % was lost?

What is your income per season from farming? Per year?

Do you do any other activities to earn money? What activities?

How much do you earn per season? Per year?

Questions to be answered for each crop whose residues can be used in the gasifier *(explain)*

When are the harvest seasons? What is the yield for each season?

<table>
<thead>
<tr>
<th>CROP 1</th>
<th>CROP 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>What quantities of residues do you get from 1 bag of crop?</td>
<td></td>
</tr>
<tr>
<td>How much of your crop do you sell with the residues?</td>
<td></td>
</tr>
<tr>
<td>Where do you sell that to?</td>
<td></td>
</tr>
<tr>
<td>What is the price/bag?</td>
<td></td>
</tr>
<tr>
<td>Do you sell residues? To who? In what quantities? At what price? Has this price changed in the past 5 years?</td>
<td></td>
</tr>
<tr>
<td>When do you process you crop (after harvest)?</td>
<td></td>
</tr>
<tr>
<td>What do you do with the residues? Mulch, feed, cooking, supplying gasifier? (Y/N)</td>
<td></td>
</tr>
<tr>
<td>If No- Would you be willing to provide residues for the gasifier?</td>
<td></td>
</tr>
<tr>
<td>Do you know of any place where residues are collected and/or stored? Any place they could</td>
<td></td>
</tr>
</tbody>
</table>
2A. IF YES currently supplying with residues

Do you use fertilizers or compost?

- [ ] Yes
- [ ] No

What quantities are you supplying to the gasifier?

How are those being collected? Do residues get wet before being picked up?

What prices or arrangement? Any issues?

3. Firewood and Charcoal Market

What type of fuel do you use for cooking?

- [ ] Wood
- [ ] Charcoal
- [ ] Coal
- [ ] Biomass
- [ ] Other (please specify)
What quantity is required for your household per day (average)?

If you use firewood, where does it come from?
Local forests or plantations? Farmlands, farm boundaries? Imported from outside of community? From where?

Do you or the farmer co-operative export/sell wood? Y / N

If yes how much do you sell? How much does the whole community sell in combination? To who? What quantities? What price? Has this price changed in the last 5 years? For what purposes?

4. Growing Trees
4.1 Wood Biomass Initiative

Are you aware of the program with Vi to supply the gasifier? Y/ N

Did you participate in trainings? Why or why not?

How many trainings?

What did you learn about? Water conservation, tree planting, harvesting, soil benefits?
<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did you grow any trees? Are you/were you already growing trees? Why or why not?</td>
<td></td>
</tr>
<tr>
<td>What challenges did you have in growing trees?</td>
<td></td>
</tr>
<tr>
<td>If we bring seeds would you accept to plant re-growing trees? Would you be willing to grow trees for the gasifier with some help (seedlings, training/education?)</td>
<td></td>
</tr>
</tbody>
</table>

### 4.4 Wood Biomass Monitoring

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>How many trees are you growing? What species? Do you know how many trees of each species?</td>
<td></td>
</tr>
<tr>
<td>On what site(s)? What area? What was happening on that land before growing trees?</td>
<td></td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Can I visit the site?</td>
<td></td>
</tr>
<tr>
<td>What is your plan for the trees currently growing? When will it be ready</td>
<td></td>
</tr>
<tr>
<td>to harvest? If selling what price?</td>
<td></td>
</tr>
<tr>
<td>Have you collected seeds? For which species? Are you interested in</td>
<td></td>
</tr>
<tr>
<td>collecting seeds? Do you have training on collecting seeds?</td>
<td></td>
</tr>
<tr>
<td>Pricing and collection- How is biomass processed (cut, dried, delivered</td>
<td></td>
</tr>
<tr>
<td>to site) and at what prices?</td>
<td></td>
</tr>
</tbody>
</table>

### 4.1 New Woodlots

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you have spare land to grow trees (hedgerows?)? How is this land</td>
<td></td>
</tr>
<tr>
<td>being used currently?</td>
<td></td>
</tr>
<tr>
<td>Any marginal land available not suitable for farming?</td>
<td></td>
</tr>
<tr>
<td>Are there private or communal dedicated woodlots in the village? Where?</td>
<td></td>
</tr>
</tbody>
</table>
### 4.2 Agroforestry

Do you know what agroforestry is? Do you practice agroforestry?

*Explain: we provide training and materials for you to grow biomass as part of your farm and then buy the biomass*

Growing hedgerows, intercropping, growing trees on fallow land

Do you practice fallow agriculture?

If yes how long do you leave land fallow?

How much land is fallow?

Would you be willing to have trees/shrubs on you fallow? (Plants that would die out after 1-2 years and are planted to increase soil fertility.)

### 4.3 Land for lease/sale

Do you have land for lease or sale? Where is this land?

If yes what are the land leasing prices? Cost/acre and total field size? What are the land purchase prices? Cost/ha and total field size?
B. Interview guides

**Questionnaire for Cooperatives/Community Leaders**

Date ______/_______/_______

(Adapted from Joerg 2012)

### 1. Background Information

<table>
<thead>
<tr>
<th>Name:</th>
<th>Age:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Information:</td>
<td></td>
</tr>
<tr>
<td>Site Location:</td>
<td>District:</td>
</tr>
<tr>
<td>Type of Group:</td>
<td>Name of Group:</td>
</tr>
<tr>
<td>Position within group:</td>
<td>Length of service:</td>
</tr>
</tbody>
</table>

### 2. Local Population Information

<table>
<thead>
<tr>
<th>Area population:</th>
<th>Within 4-5km of gasifier site:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of farmers:</td>
<td>% member of co-operative:</td>
</tr>
<tr>
<td>Average size of farms:</td>
<td>Total area of farms in community:</td>
</tr>
<tr>
<td>Main crops grown and how much of each?</td>
<td></td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>How many farmers are growing (supply crop)?</td>
<td></td>
</tr>
<tr>
<td>In what amount (total area planted?):</td>
<td></td>
</tr>
<tr>
<td>How many times do people plant (supply crop) in a year? What are the planting seasons? Harvest seasons?</td>
<td></td>
</tr>
<tr>
<td>What is the average yield/acre planted?</td>
<td></td>
</tr>
<tr>
<td>What quantity of residues can you get from one bag of crop?</td>
<td></td>
</tr>
<tr>
<td>Where do people get their crops processed? When?</td>
<td></td>
</tr>
<tr>
<td>What are the agricultural practices of farmers? Do farmers use pesticides and/or fertilizers?</td>
<td></td>
</tr>
<tr>
<td>What is the average income for this community?</td>
<td></td>
</tr>
</tbody>
</table>

3. Cooperative/Association Questions
<table>
<thead>
<tr>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>How many members in the association/cooperative?</td>
</tr>
<tr>
<td>What area does the group represent?</td>
</tr>
<tr>
<td>How long has the group been operating?</td>
</tr>
<tr>
<td>Who is the Chairman? What is the leadership's role?</td>
</tr>
<tr>
<td>What is the role of the group and its members?</td>
</tr>
<tr>
<td>What is the total yield of (supply crop) of the group? Do you keep a book of harvest records?</td>
</tr>
<tr>
<td>Does the cooperative supply pesticides or fertilizers to members?</td>
</tr>
<tr>
<td>What is the current market price for firewood and charcoal per bundle/bag? Has this price changed in the past 5 years?</td>
</tr>
</tbody>
</table>
Supply Monitoring Questions

What is the current supply arrangement for the gasifier biomass supply? Who is responsible for ensuring a stable supply? What has been done to ensure a stable supply?

Where is the supply for the gasifier coming from? Does this change throughout the year? How?

What will happen when agro-processing starts, fees for electricity start, will payment for the biomass be expected?

Woody biomass

What is the status of the wood biomass being grown? What price do you think is fair for the woody biomass? If there is woody biomass that cannot be sold to the gasifier, do you have other uses for it?
F. Weighting Instructions

Biomass Supply Chain Criteria Weighting Instructions

The criteria and indicators in the attached excel worksheet are being used to evaluate how sustainable different biomass feedstocks are for a small scale bio-energy system working to generate electricity in rural off-grid scenarios. Possible biomass supplies could include purchasing wood locally, growing trees in woodlots or an agroforestry system, using agricultural residues such as maize cobs, rice husks or coffee shells.

Our team is looking to understand how giving different levels of importance, or weights, to the criteria involved in measuring the overall sustainability of different supply options, will change the performance of the supplies. For example, if cost is viewed as most important and therefore weighed highest, which supply system is the most sustainable? If environmental criteria are weighted most heavily does that change which supply is most appropriate?

We would like your perspective regarding what criteria matter most when making a supply chain decision for a bio-energy system in this rural context. Please find the included criteria weighting worksheet and take a few minutes to review the criteria at each level of the decision tree. A PDF figure list is also included if you care to view the criteria and indicators in a diagram form to better understand the different levels involved.

Once you have reviewed the criteria and indicators, please assign weights starting from the left-most, or most broad level, criteria (Reliability, Social/Economic, Environmental, Cost/Quality). Weights can range from 1-100, moving by 10’s, with 1 being “of almost no importance” and 100 representing “critical importance”. You can assign the same weight to more than one criteria. They will be normalized later.
Continue moving to the right along the decision tree, assigning weights to the criteria and indicators involved in the decision. If you have any questions regarding the process or project please contact Deandra Perruccio at dperrucc@uvm.edu.

Thank you for your time and opinions

E. Analytica Model

Available Online through Pamoja Cleantech
6.1 MCDA as a decision tool

MCDA literature is careful to clearly define best practice in the use of MCDA, and dispel common myths regarding its capabilities and purpose. As Belton states “The aim of MCDA should be, and principal benefit is, to facilitate decision makers understanding of the problem faced, about their own, other parties’, and organizational priorities, values, and objectives, and through exploring these in the context of the problem to guide them in identifying a preferred course of action” (Belton and Stewart, 2002).

Results highlight that this model is able to provide valuable information to educate decision makers in comparing the sustainability of supply chain options as well as understanding their subjective priorities and how differing goals impact the definition of sustainability within the system. The results also demonstrate that the value of MCDA lies within the process rather than any prescriptive recommendation. Critiques of MCDA claim it is a prescriptive approach, prohibiting the nuanced understanding required when considering complex problems. French, in response, describes decision analysis as a delicate and subtle tool that helps decision makers better understand their beliefs and preferences, provides a language and formalism for the decision process, and facilitates communication between stakeholders (French, 1989). Therefore emphasis must be intentionally directed at creating and facilitating a robust process (Zeleny, 1982).

MCDA models have also been criticized as too simplistic. There is a misunderstanding within that assumption about the simple model which ignores the involved process leading to simplicity. In MCDA simple models useful to the decision process emerge from distilling key factors in a transparent way that generates better understanding (Belton and Stewart, 2002). The complexity, rigor, and highly involved learning process inherent in this “science of synthesis” should not be understated by deceivingly simple models as their simplicity serves a purpose of refining the decision problem, informed by participatory learning during model generation itself.

The process leading to clear and simple models brings us to an important limitation of MCDA when considering its use in resource poor contexts. Important considerations when evaluating methodologies for use in emerging economies is availability of resources, data, and inclusion of local stakeholders. MCDA as a field can be highly technical, frequently employing experts with high levels of training from countries with developed Management Science and Systems programs. These projects therefore can
become resource and time-intensive. They can also suffer from lack of authentic relationship building and local capacity or expertise and can be challenging for local private and public entities to implement well.

Well calibrated and highly accurate models rely heavily on the availability of frequency data as well as research informing development of indicators and model structure. The lack of institutional and private sector infrastructure in some countries limits access to good information with which to build and calibrate a model. Probability distributions and sensitivity analysis can allow models to more accurately reflect the knowledge we have about a subject, but without good data that knowledge retains a high degree of entropy and is less useful for predicting outcomes (Chrisman, 2008).

The lack of readily available data points for model calibration and analysis creates another limitation especially relevant when discussing this particular model, which relies heavily on expert opinions and qualitative analysis; the existence of cognitive bias. Cognitive biases occur when people in decision-making positions use common psychological heuristics to come to conclusions which can end up skewing figures resulting in inaccurate predictions (Belton & Stewart, 2002). Common cognitive biases include overconfidence, anchoring, motivational bias, and denial of uncertainty (Chrisman, 2008). The MCDA decision tool offers a useful way to apply the Sustainability Assessment Framework In comparison to alternative modeling methods which often require more exact estimations and are less able to explicitly incorporate uncertainty, MCDA allows the identification and consideration of important factors across social, economic, and environmental spheres. It can produce useful information through the decision support process, and does not require high levels of accuracy within data but can be used with qualitative assessments and still be an extremely useful exercise. As mentioned above the key strengths in this methodology lie in the process of developing and using the structure, which means it can be a useful tool without the need for excessive investments of resources and time.

However, the complicated nature of the analysis does impact its usability, or ability to be accessed by practitioners. Pairing the Sustainability Assessment with the MCDA decision tool increases the amount and accuracy of information informing the decision process and develop results with academic rigor and therefore useful for knowledge generation, academic debate, and potentially donor project evaluation; qualitative assessment of the criteria laid out within the SA tool in the form of a report may achieve similar results better suited to the resources and accessibility of practitioners. Additionally honing down indicators in light of priorities can help target fewer resources and create a clearer message for small scale system analysis. While a number of criteria were synthesized and measurement techniques improved through the implementation process, the case study
addressed in this thesis represents a small scale system with potentially lower available resources for project planning and highlights the importance of identifying fewer key indicators for analysis. As seen in the article sensitivity analysis can help identify key indicators.

6.2 Biomass Gasification as a rural electrification strategy

While effectively managed systems can offer positive environmental, economic, and social synergies, caution must be taken to ensure these systems alleviate rather than contribute to biomass demand pressures causing high deforestation rates (Okello et al., 2013; Harrison et al., 2010; Gallagher, 2008). Significant management capacity and resources are needed to achieve sustainable bio-energy systems (Harrison et al., 2010a).

Biomass gasification certainly has potential for significant environmental and social benefits in addition to economic viability; however the sustainability of a bio-energy system at any scale is highly dependent on its planning, implementation and management. Questions of GHG balances as well as links between biomass production and deforestation or food competition are valid concerns (Amezega et al., 2010 pg 2; Buchholz & Volk, 2012; Maltoglou et al., 2013), all of which highlight the need for robust planning and assessment tools to provide inclusive and transparent evaluation of sustainability objectives in relation to any bio-energy system (Amezega et al., 2010; Buchholz et al., 2008). This research provides a framework within which the sustainability of projects can be evaluated, specifically small scale projects in countries with challenging socio-technical infrastructure. Using MCDA in conjunction with the burgeoning Sustainability Assessment process to incorporate assessment methodologies best suited to social, economic, and environmental criteria relevant in each context is therefore critical for stakeholders to adeptly define, understand, and evaluate the sustainability of individual projects.

There is currently a wide array of criteria and processes that have been developed (buchholz 2009, other sources), and little consensus on SA methods (Harrison et al., 2010b). Consensus in this management approach may be unachievable and undesirable for practitioners, donor agencies, and the academic community (Grace and Pope, 2006). In lieu of the unrealistic expectations of standard indicators and prescriptive measurements, this research suggests the importance of well-designed tools which can synthesize important information, encourage stakeholder participation and learning, and improve the decision making process. Assessment transparency, stakeholder participation, and support through government regulation can further ensure truly sustainable outcomes as defined by those impacted.
References


Beddington, J., Asaduzzaman, M., Clark, M., Fernández, A., Guillou, M., Jahn, M., Erda, L., Mamo, T., Bo, NV., Nobre, CA., Scholes, R., Sharma, R., Wakhungu, J. (2012. Food Security in the Face of Climate Change: Final Report From the Commission on Sustainable Agriculture and Climate Change. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark


Article Figures and Tables Inserts

Article Submission Figures and Captions

![Figure 17 Framework Organizational Structure](image1.png)

Figure 17 Framework Organizational Structure

![Figure 18 Criteria and Sub-Criteria Visual](image2.png)

Figure 18 Criteria and Sub-Criteria Visual
Figure 19 Reliability Decision Tree
Figure 20 Social/Economic Impacts Decision Tree
Figure 21 Environmental Impacts Decision Tree
Figure 22 Costs/Quality Decision Tree
Figure 23 Model Mechanics

Figure 24 Criteria Weights by Expert

Normalized scores $\times$ Normalized weights = Weighted Scores

- Indicator 1 score 80 Indicator 1 weight 40 = 16
- Indicator 2 score 15 Indicator 2 weight 40 = 3
- Indicator 3 score 5 Indicator 3 weight 60 = 3

(Zero normalization) Summed Sub-criteria Score 22

Summed Sub-criteria Score $\times$ Normalized weights = Weighted Scores

- Sub-criteria 1 score 22 Sub-criteria 1 weight 70 = 15.4
- Sub-criteria 2 score 46 Sub-criteria 2 weight 30 = 13.8

Summed Criteria Score 29.2
Figure 25 Scenario Rankings by Expert

Figure 26 Site 1. Tiribogo Criteria Scores by Expert
Figure 27 Site 2 Sekanyonyi Criteria Scores by Expert

Figure 28 Years in Operation Probability Distributions
Figure 29 Productivity Probability Distributions

Note. $u = \text{micro } (10^{-6})$, $m = \text{milli } (10^{-3})$. 
Figure 30 Tornado Analysis Development Weighting Scheme 80-120% Variation
Figure 31 Radar Graphs
Article Submission Tables

Table 7 Equations for Normalization and Scoring

<table>
<thead>
<tr>
<th>Function</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1. Indicator score normalization</td>
<td>$100 \times \left(\frac{\text{attribute score} - \text{best level}}{\text{best level} - \text{worst level}}\right)$</td>
</tr>
<tr>
<td>Step 2. Weight normalization</td>
<td>$100 \times \left(\frac{\text{given value}}{\sum \text{all values}}\right)$</td>
</tr>
<tr>
<td>Step 3. Score weighting</td>
<td>$(\text{normalized weight} \times \text{normalized score}) / 100$</td>
</tr>
<tr>
<td>Step 4. Scores summation</td>
<td>$\sum \text{weighted scores}$</td>
</tr>
</tbody>
</table>

Table 8 Criteria Weights by Expert

<table>
<thead>
<tr>
<th>Expert Category</th>
<th>I. (R) Reliability</th>
<th>II. (SE) Social/Economic Impacts</th>
<th>III. (E) Environmental Impacts</th>
<th>IV. (C/Q) Costs/Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Expert</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Project Manager</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Development Expert</td>
<td>30</td>
<td>40</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>
Article Submission Appendices Figures

**Figure A.32 SA Process Visual**

**Figure B.1 Business Expert Weighting of R1, R2, R3**
Figure B.2 Development Expert Weighting of R1, R2, R3

Figure B.3 Business Expert Reliability Score Breakdown by Sub-Criteria
Figure B.4 Development Expert Reliability Score Breakdown by Sub-Criteria

Figure B.12 Business Expert Weighting R1 Sub-Criteria
**Figure B. 13 Development Expert Weighting R1 Sub-Criteria**

**Figure B. 14 Business Expert Weighted Scores Breakdown R1**
Figure B. 15 Development Expert Weighted Scores Breakdown R1
Figure B. 16 Tornado Analysis Business Weighting Scheme 80-120% Variation Range
Figure B. 17 Tornado Analysis Development Weighting Scheme 80-120% Range
Figure B. 18 Tornado Analysis Development Weighting Scheme 40%-160% Variation Range
### Model Rating Methods, Source Details and Scaling

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating Method</th>
<th>Source Details</th>
<th>Best</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. (R) RELIABILITY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>R 1 Supplier Reliability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>R 1.1 Level of Organization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1.1.1 Years in operation</td>
<td>number of years in operation</td>
<td>20</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R1.1.2 Productivity</td>
<td>kg/year. Overall estimate of supplier(s) total.</td>
<td>maize survey- kg/yr total production, agro-# trees planted * ave kg/tree</td>
<td>200,000</td>
<td>30</td>
</tr>
<tr>
<td>R1.1.3 Finances</td>
<td>ordinal scale 1-10</td>
<td>Pamoja manager</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>R1.1.4 Member/customer satisfaction</td>
<td>ordinal scale 1-10</td>
<td>Pamoja manager</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>R1.2 Supplier Numbers</td>
<td>ordinal scale 1-10</td>
<td>Pamoja manager</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>vR1.3 Contract</td>
<td>yes/no 10=yes, 0.01=no</td>
<td>Pamoja manager</td>
<td>10</td>
<td>0.01</td>
</tr>
<tr>
<td>R1.4 Supplier Proximity</td>
<td>km supply range</td>
<td>Pamoja manager</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td><strong>R2 Supply Dynamics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>R2.1 Variability of Supply Availability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2.1.1 number of harvest seasons/year</td>
<td>1-4 times/year</td>
<td>[1]</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>R2.1.2 shock impacts last 5 years</td>
<td>percentage of crop loss average</td>
<td>survey responses</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>
### II. (SE) SOCIAL/ECONOMIC IMPACTS

#### SE 1. Value Creation/Distribution

**SE 1.1 Income generation**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating Method</th>
<th>Source Details</th>
<th>Best</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1.1.1 percent farmers participating</td>
<td>percentage of surveyed respondents participating</td>
<td>survey responses (see SE scoring tab)</td>
<td>100</td>
<td>0.01</td>
</tr>
<tr>
<td>SE1.1.2 net earnings/farmer</td>
<td>total supplied * price/kg/total farmers</td>
<td>Pamoja manager</td>
<td>100000</td>
<td>0.01</td>
</tr>
<tr>
<td>SE1.1.3 other income (trans., processing, storage, maintenance)</td>
<td>total other income + wage/number of employees</td>
<td>Pamoja manager</td>
<td>1000000</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**SE 1.2 Income distribution**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating Method</th>
<th>Source Details</th>
<th>Best</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1.2.1 standard deviation of supply amounts</td>
<td>high standard deviation indicates high variability in supplier amounts</td>
<td>survey responses, manager records</td>
<td>0.01</td>
<td>500</td>
</tr>
</tbody>
</table>
SE1.2.2 income percentage increases
net earnings/current total income-(ave)*
survey responses (see SE scoring tab)

50  0.01

SE 1.3 Social Capital
SE1.3.1 job creation + type
scoring rubric
company records, partner records (see SE scoring)
100  1

SE1.3.2 # trainings conducted
number of reported trainings related to skill improvement
Pamoja manager, partner records
100  1

SE1.3.3 # attendees
total number of attendees to skill development trainings/meetings
partner records
1000  1

SE2. Resource competition

SE2.1 Land-use competition

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating Method</th>
<th>Source Details</th>
<th>Best</th>
<th>Worst</th>
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<tbody>
<tr>
<td>SE2.1.1 high/low risk in supply use causing resource competition beyond boundary</td>
<td>ordinal scale 1-10</td>
<td>Pamoja manager</td>
<td>1</td>
<td>10</td>
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<tr>
<td>SE2.1.2 high/low risk in competing with fertile land</td>
<td>ordinal scale 1-10</td>
<td>Pamoja manager</td>
<td>1</td>
<td>10</td>
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<tr>
<td>SE2.1.3 change in land-use</td>
<td>percentage of acres converted from forest to ag as due to supply</td>
<td>survey responses</td>
<td>0.01</td>
<td>100</td>
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SE 2.2 Competing uses

<table>
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<th>Worst</th>
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<tbody>
<tr>
<td>SE2.2.1 How much is used (percentage of total)</td>
<td>amount used/total amount/yr</td>
<td>[5]</td>
<td>0.01</td>
<td>100</td>
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<tr>
<td>SE2.2.2 Competing demand</td>
<td>manager ordinal scoring</td>
<td>Pamoja manager</td>
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III. (E) ENVIRONMENTAL IMPACTS

E1. Deforestation/forest degradation

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<th>Best</th>
<th>Worst</th>
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</thead>
<tbody>
<tr>
<td>E1.1 Land-use change risk</td>
<td>high or low risk for deforestation</td>
<td>Pamoja manager</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>E1.2 Trees planted</td>
<td>number trees planted</td>
<td>survey responses</td>
<td>1000</td>
<td>1</td>
</tr>
</tbody>
</table>
E1.3 mitigation by products | yes/no 10=yes, 1=no | manager interviews | 10 | 1
E1.4 Leakage score | high/ low risk for supply resource pressure beyond community boundary | Pamoja manager | 1 | 10
E1.5 supply source certainty and contribution to deforestation | high/low certainty of supply source and contribution to deforestation pressure | Pamoja manager | 10 | 1

**E2. Soil Quality**

*E2.1 Nutrient cycle*

E2.1.1 change in nat fertilizer availability | removal or addition of fertilizer | Pamoja manager | 10 | 1
E2.1.2 number of trees, n fixing? Leaves? | number of trees planted | Pamoja manager | 10000 | 1
E2.1.3 degraded land restoration | | Pamoja manager | 10 | 1

*E2.2 Soil Structure*

E2.2.1 change in organic matter? | removal or addition of fert. 1=poowr, 10=new forest | survey responses, [6] | 10 | 1

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating Method</th>
<th>Source Details</th>
<th>Best</th>
<th>Worst</th>
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</thead>
<tbody>
<tr>
<td>E2.2.2 tree coverage 1=ag 10=new forest</td>
<td># trees planted</td>
<td>survey responses, partner records</td>
<td>10</td>
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<tr>
<td>E2.2.3 perennial crops planted or no till ag?</td>
<td>acres changed to per. Or no till</td>
<td>survey</td>
<td>10</td>
<td>1</td>
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</table>

**E3. Water table**

E3.1 water requirements for supply | | [1], [2] | 1 | 5000 |
E3.2 rainwater harveting technology used? | y/n 10=yes, 1=no | survey responses and observation | 10 | 1 |
E3.3 degraded land restoration | y/n 10=yes, 1=no | survey responses, partner records | 10 | 1 |

**E4. Biodiversity**


### E4. Use of native species
- Use of native species: y/n 10=yes, 1=no
- Manager interviews, partner records

### E5. Sustainable farming practices

<table>
<thead>
<tr>
<th>E5.1 Number of trainings</th>
<th>Number of trainings</th>
<th>Partner records</th>
<th>20</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5.2 Number of attendees to trainings</td>
<td>Number of attendees to trainings</td>
<td>Partner records</td>
<td>500</td>
<td>0.001</td>
</tr>
<tr>
<td>E5.3 Number of SF practices being implemented</td>
<td>Number of SF practices being implemented</td>
<td>Survey responses</td>
<td>85</td>
<td>0.001</td>
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<tr>
<td>E5.4 Percentage of people aware of SFP</td>
<td>Percentage of people aware of SFP</td>
<td>Survey responses, observations</td>
<td>100</td>
<td>0.001</td>
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</tbody>
</table>

### E6. Carbon cycle
- Assumed neutral if not contributing to deforestation: ordinal scale 1-10

### IV. COSTS/QUALITY

<table>
<thead>
<tr>
<th>CQ 1. System Costs</th>
</tr>
</thead>
</table>

- **CQ1.1 Storage costs**: ugx/m³
  - Source: Pamoja manager
  - Best: 50
  - Worst: 10000

- **CQ1.2 Capital costs for start up?**: total capital costs, USD
  - Source: Pamoja manager
  - Best: 30000
  - Worst: 100000

- **CQ1.3 Market prices**: prices for supply, UGX/kg
  - Source: Pamoja manager
  - Best: 0.01
  - Worst: 1000

### Table of Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating Method</th>
<th>Source Details</th>
<th>Best</th>
<th>Worst</th>
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<tr>
<td>CQ1.4 Processing</td>
<td>Costs for processing, UGX/kg</td>
<td>Pamoja manager</td>
<td>0.01</td>
<td>500</td>
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<tr>
<td>CQ1.5 Transportation</td>
<td>Cost/mass, UGX/kg</td>
<td>Pamoja manager</td>
<td>0.01</td>
<td>100</td>
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<tr>
<td>CQ1.6 Training</td>
<td>Total training costs, USD</td>
<td>Pamoja manager</td>
<td>500</td>
<td>6000</td>
</tr>
<tr>
<td>CQ1.7 Maintenance &amp; Management</td>
<td>$/kWh</td>
<td>Pamoja manager</td>
<td>0.01</td>
<td>0.1</td>
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<tr>
<td>CQ1.8 Whole system costs</td>
<td>LCOE (USD cents)</td>
<td>Pamoja manager</td>
<td>10</td>
<td>50</td>
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## CQ2. Quality of feedstock

<table>
<thead>
<tr>
<th>CQ2.1 moisture content</th>
<th>ave. moisture content assumed at 20%</th>
<th>[6]</th>
<th>0.01</th>
<th>100</th>
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</thead>
<tbody>
<tr>
<td>CQ2.2 processing requirements</td>
<td>high to low processing involvement</td>
<td>[7], [8]</td>
<td>1</td>
<td>10</td>
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<tr>
<td>CQ2.3 energy density</td>
<td>kwh/kg</td>
<td>[8]</td>
<td>10</td>
<td>0.01</td>
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<tr>
<td>CQ2.4 ash content</td>
<td>percentage</td>
<td>[9]</td>
<td>0.01</td>
<td>100</td>
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<tr>
<td>CQ2.5 machine life impact</td>
<td>Ordinal scale 1-10</td>
<td>Pamoja manager</td>
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<td>10</td>
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</tbody>
</table>

* Note. Does not currently include management and operational salaries

### Table A.2
*Indicator Scores by Scenario*

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<tr>
<th>Criteria</th>
<th>Best</th>
<th>Worst</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Tiribogo</td>
<td>Tiribogo</td>
<td>Ssek. Maize</td>
<td>Ssek. Agroforest</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maize cobs</td>
<td>Agroforest</td>
<td>cobs</td>
<td>Agroforest</td>
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<td>I. (R) RELIABILITY</td>
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<td>R 1 Supplier Reliability</td>
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<td>R 1.1 Level of Organization</td>
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<tr>
<td>R1.1.1 Years in operation</td>
<td>20</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>10</td>
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<tr>
<td>R1.1.2 Productivity</td>
<td>200,000</td>
<td>30</td>
<td>1,410</td>
<td>1,570</td>
<td>1,510</td>
<td>1,990</td>
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<tr>
<td>R1.1.3 Finances</td>
<td>10</td>
<td>1</td>
<td>7</td>
<td>2</td>
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<td>4</td>
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<tr>
<td>R1.1.4 Member/customer satisfaction</td>
<td>10</td>
<td>1</td>
<td>6</td>
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<td>6</td>
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<td>R1.2 Supplier Numbers</td>
<td>10</td>
<td>1</td>
<td>7</td>
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<td>R1.3 Contract</td>
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<td>0.01</td>
<td>10</td>
<td>0.01</td>
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<td>R1.4 Supplier Proximity</td>
<td>13</td>
<td>3</td>
<td>5</td>
<td>10</td>
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<td>R2 Supply Dynamics</td>
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<td>R2.1 Variability of Supply Availability</td>
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<tr>
<td>R2.1.1 number of harvest seasons/year</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>2</td>
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<tr>
<td>R2.1.2 shock impacts last 5 years</td>
<td>1</td>
<td>100</td>
<td>35.87</td>
<td>35.87</td>
<td>44.67</td>
<td>44.67</td>
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<tr>
<td>R2.1.3 crop productivity trends last 20 years</td>
<td>10</td>
<td>1</td>
<td>8</td>
<td>3</td>
<td>8</td>
<td>3</td>
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<td>R2.2 storage capacity ratio</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>60</td>
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<td>R3 Competing Demand Dynamics</td>
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<td>R3.1 Population use trends</td>
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<td>R3.1.1 population growth rate</td>
<td>0.01</td>
<td>5</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
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<td>R3.1.2 % being used by population</td>
<td>0.01</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<td>R3.1.3 % population using personal</td>
<td>0.01</td>
<td>100</td>
<td>60</td>
<td>50</td>
<td>87</td>
<td>50</td>
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<td>R3.2 Competing business trends</td>
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<td>R3.2.1 market price changes</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>11</td>
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<td>II. (SE) SOCIAL/ECONOMIC IMPACTS</td>
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<td>SE 1. Value Creation/Distribution</td>
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<td>SE 1.1 Income generation</td>
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<td>SE1.1.1 percent farmers participating</td>
<td>100</td>
<td>0.01</td>
<td>30</td>
<td>27</td>
<td>22</td>
<td>33</td>
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<td>Value1</td>
<td>Value2</td>
<td>Value3</td>
<td>Value4</td>
<td>Value5</td>
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<td>--------</td>
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<td>SE1.1.2</td>
<td>net earnings/farmer</td>
<td>100000</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>10000</td>
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<tr>
<td>SE1.1.3</td>
<td>other income (trans., processing, storage, maintenance)</td>
<td>1000000</td>
<td>0.01</td>
<td>2000</td>
<td>0</td>
<td>5000</td>
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<td>SE 1.2 Income distribution</td>
<td>standard deviation of supply amounts</td>
<td>0.01</td>
<td>500</td>
<td>64</td>
<td>241.32</td>
<td>8.48</td>
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<td>SE1.2.2</td>
<td>income percentage increases</td>
<td>50</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<td>SE 1.3 Social Capital</td>
<td>job creation + type</td>
<td>100</td>
<td>1</td>
<td>16</td>
<td>41</td>
<td>16</td>
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<td>SE1.3.2</td>
<td># trainings conducted</td>
<td>100</td>
<td>1</td>
<td>2</td>
<td>33</td>
<td>1</td>
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<td>SE1.3.3</td>
<td># attendees</td>
<td>1000</td>
<td>1</td>
<td>20</td>
<td>415</td>
<td>20</td>
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<td>SE2. Resource competition</td>
<td>SE 2.1 Land-use competition</td>
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<td>SE2.1.1</td>
<td>high/low risk in supply use causing resource competition beyond boundary</td>
<td>1</td>
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<td>high/low risk in competing with fertile land</td>
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<td>10</td>
<td>1</td>
<td>5</td>
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<td>SE2.1.3</td>
<td>change in land-use</td>
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<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SE 2.2 Competing uses</td>
<td>SE2.2.1 How much is used (percentage of total)</td>
<td>0.01</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<td>SE2.2.2</td>
<td>Competing demand</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>III. (E) Environmental Impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1. Deforestation/degradation</td>
<td>E1.1 Land-use change risk</td>
<td>1</td>
<td>10</td>
<td>7</td>
<td>9</td>
<td>7</td>
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<tr>
<td>E1.2</td>
<td>Trees planted</td>
<td>1000</td>
<td>1</td>
<td>0</td>
<td>615</td>
<td>0</td>
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<tr>
<td>E1.3</td>
<td>mitigation by products</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>1</td>
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<td>E1.4</td>
<td>Leakage score</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>8</td>
<td>1</td>
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<tr>
<td>E1.5</td>
<td>supply source certainty and contribution to deforestation</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
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<tr>
<td>E2. Soil Quality</td>
<td>E2.1 Nutrient cycle</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>E2.1.1</td>
<td>change in nat fertilizer availability</td>
<td>10</td>
<td>1</td>
<td>4</td>
<td>10</td>
<td>4</td>
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<tr>
<td>E2.1.2</td>
<td>number of trees, n fixing? Leaves?</td>
<td>10000</td>
<td>1</td>
<td>1</td>
<td>615</td>
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<td>E2.1.3</td>
<td>degraded land restoration</td>
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<td>1</td>
<td>1</td>
<td>8</td>
<td>1</td>
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<tr>
<td>E2.2 Soil Structure</td>
<td>E2.2.1 change in organic matter?</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>E2.2.2</td>
<td>tree coverage 1=ag 10=new</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>
forest
E2.2.3 perennial crops/no till ag. 10 1 1 1 1 1 1

**E3. Water table**

| E3.1 water requirements for supply | 1 | 5000 | 1300 | 3,000 | 1300 | 3,000 |
| E3.2 rainwater harvesting technology used? | 10 | 1 | 1 | 10 | 1 | 10 |
| E3.3 degraded land restoration | 10 | 1 | 1 | 10 | 1 | 10 |

**E4. Biodiversity**

| E4.1 use of native species | 10 | 1 | 5 | 8 | 5 | 8 |
| E4.2 intercropping and hedgerows (vs woodlots or ag?) | 10 | 1 | 1 | 10 | 1 | 10 |

**E5. Sustainable farming practices**

| E5.1 number of trainings | 20 | 0.001 | 0 | 33 | 0 | 20 |
| E5.2 number of attendees to trainings | 500 | 0.001 | 0 | 415 | 0 | 706 |
| E5.3 number of SF practices being implemented | 85 | 0.001 | 9 | 46 | 7 | 46 |
| E5.4 % people aware of SFP | 100 | 0.001 | 57 | 57 | 67 | 67 |

**E6. carbon cycle**

| E6.1 assumed neutral if not contributing to deforestation | 1 | 10 | 1 | 1 | 1 | 1 |

**IV COSTS/QUALITY**

<table>
<thead>
<tr>
<th><strong>CQ 1. System Costs</strong></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<td>CQ1.1 storage costs</td>
<td>50</td>
<td>10000</td>
<td>2000</td>
<td>2000</td>
<td>5000</td>
<td>5000</td>
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<tr>
<td>CQ1.2 capital costs for start up?</td>
<td>30000</td>
<td>100000</td>
<td>70000</td>
<td>70000</td>
<td>40000</td>
<td>40000</td>
</tr>
<tr>
<td>CQ1.3 market prices</td>
<td>0.01</td>
<td>1000</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CQ1.4 processing</td>
<td>0.01</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CQ1.5 transportation</td>
<td>0.01</td>
<td>100</td>
<td>40</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>CQ1.6 training</td>
<td>500</td>
<td>6000</td>
<td>500</td>
<td>3400</td>
<td>500</td>
<td>3400</td>
</tr>
<tr>
<td>CQ1.7 maintenance &amp; management</td>
<td>0.01</td>
<td>0.1</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
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<tr>
<td>CQ1.8 whole system costs</td>
<td>10</td>
<td>50</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
</tbody>
</table>

**CQ2. Quality of feedstock**

| CQ2.1 moisture content | 0.01 | 100 | 20 | 20 | 20 | 20 |
| CQ2.2 processing requirements | 1 | 10 | 3 | 6 | 3 | 6 |
| CQ2.3 energy density | 10 | 0.01 | 3.5 | 4.3 | 3.5 | 4.3 |
| CQ2.4 ash content | 0.01 | 100 | 11.65 | 1.3 | 11.65 | 1.3 |
| CQ2.5 machine life impact | 1 | 10 | 6 | 5 | 2 | 1 |
Table A.3

*Standards Considered in Framework Development*

**Standards and Organizations**

<table>
<thead>
<tr>
<th>Standards and Organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundtable on Sustainable Biofuels</td>
</tr>
<tr>
<td>Council on Sustainable Biomass Production</td>
</tr>
<tr>
<td>Natureland Standards on Production</td>
</tr>
<tr>
<td>East African Organic Products Standards</td>
</tr>
<tr>
<td>Forest Stewardship Council</td>
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<tr>
<td>Program for the Endorsement of Forest Certification</td>
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<tr>
<td>Fairtrade Standards for Timber and Forest Enterprises</td>
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<td>Global Bioenergy Partnership</td>
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Table A.4  
Framework and Model Criteria, Sub-criteria, and Indicators

<table>
<thead>
<tr>
<th>R. Reliability Criteria</th>
<th>SE. Socio-Economic Criteria</th>
<th>E. Environmental Criteria</th>
<th>CQ. Costs/Quality Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1. Supplier Reliability</td>
<td></td>
<td>E1. Deforestation and Degradation</td>
<td>CQ1. System costs</td>
</tr>
<tr>
<td>R1.1 Level of Organization</td>
<td>SE1.1 Income Generation</td>
<td>E1.1 Land use change risk</td>
<td>CQ1.1 Storage costs</td>
</tr>
<tr>
<td>R1.1.1 Years in operation</td>
<td>SE1.1.1 Percent farmers participating</td>
<td>E1.2 Trees planted</td>
<td>CQ1.2 Capitol costs for startup</td>
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<tr>
<td>R1.1.2 Productivity</td>
<td>SE1.1.2 Net earning/farmer</td>
<td>E1.3 Mitigation byproducts</td>
<td>CQ1.3 Market prices</td>
</tr>
<tr>
<td>R1.1.3 Finances</td>
<td>SE1.1.3 Other Income</td>
<td>E1.4 Leakage score</td>
<td>CQ1.4 Processing costs</td>
</tr>
<tr>
<td>R1.4 Member/customer satisfaction</td>
<td>SE1.2 Income Distribution</td>
<td>E1.5 Supply chain certainty</td>
<td>CQ1.5 Transportation</td>
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<tr>
<td>R1.2 Supplier Numbers amounts</td>
<td>SE1.2.1 Standard deviation of supply</td>
<td>E2. Soil Quality</td>
<td>CQ1.6 Training costs</td>
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<tr>
<td>R1.3 Supply Contract</td>
<td>SE1.2.2 Income percentage increases</td>
<td>E2.1 Nutrient cycle</td>
<td>CQ1.7 Management</td>
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<tr>
<td>R1.4 Supply Proximity</td>
<td>SE1.3 Social Capital</td>
<td>E2.1.1 Change in fertilizer availability</td>
<td>CQ1.8 monitoring assessment costs</td>
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<tr>
<td>R2. Supply Dynamics</td>
<td>SE1.3.1 Job creation score</td>
<td>E2.1.2 Number of N fixing trees</td>
<td>CQ2. Quality of Feedstock</td>
</tr>
<tr>
<td>R2.1 Variability of supply availability</td>
<td>SE1.3.2 Number of trainings</td>
<td>E2.1.3 Degraded land restoration</td>
<td>CQ2.1 Moisture content</td>
</tr>
<tr>
<td>R2.1.1 Number of harvest seasons/year</td>
<td>SE1.3.3 Number of people trained</td>
<td>E2.2.1 Impact on organic content</td>
<td>CQ2.2 Processing required</td>
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<td>R2.1.2 Shock impacts</td>
<td>SE2.1 Land use competition</td>
<td>E2.2.2 Trees planted</td>
<td>CQ2.3 Energy density</td>
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<td>R2.1.3 Crop productivity trends</td>
<td>SE2.1.1 Resource competition</td>
<td>E2.2.3 Change to perennial or no till</td>
<td>CQ2.4 Ash content</td>
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<tr>
<td>R2.2 Storage capacity</td>
<td>SE2.2 Competing uses beyond boundary risk</td>
<td>E3. Water table</td>
<td>CQ2.5 Machine life impact</td>
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<tr>
<td>R3. Competing Demand Dynamics</td>
<td>SE2.2.1 Fertile land competition risk</td>
<td>E3.1 Water requirement of biomass</td>
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<td>R3.1 Population Dynamics</td>
<td>SE2.1.3 Land use change</td>
<td>E3.2 Rainwater harvesting technology</td>
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<td>R3.1.1 Population growth rate</td>
<td>SE2.2 Competing uses</td>
<td>E3.3 Degraded land restoration</td>
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<td>R3.1.2 % being used by population</td>
<td>SE2.2.1 Percentage of total being used for personal use</td>
<td>E4. Biodiversity</td>
<td></td>
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<tr>
<td>R3.1.3 population % using supply</td>
<td>SE2.2.2 Competing demand level</td>
<td>E4.1 Use of native species</td>
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<tr>
<td>R3.2 Competing Uses</td>
<td>SE2.2.2 Competing demand level</td>
<td>E4.2 Intercropping and hedgerows</td>
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<td>R3.2.1 Competing market price changes</td>
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</tr>
</tbody>
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* Carbon neutrality assumed if low leakage and competing use scores