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Sustainability Assessment Framework for Bio Waste Energy in Kenya

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Abstract
Sustainability and sustainable development are broad concepts that have continued to attract increased attention within the public and private sector thus gaining a broad acceptance as the guiding principle for both public policy and corporate strategies. *Sustainability is a technical balance between the present and future interests.* However, there are challenges in the implementation of the sustainability concept owing to the multi-dimensionality of the sustainability goal coupled with the complexity of socio-economic and biophysical systems. Sustainable energy exemplifies such a panorama. In this paper, while focusing on sustainable energy, a framework is designed for comparing the environmental, technical and socio-economic performance of different biogas systems. Furthermore, an approach for operationalizing the designed framework is proposed. Innovative aspects of the proposed framework are the development of a multi dimensional assessment system with a typology of multi criteria indicators relevant for biogas energy. In addition two main sustainability issues that could potentially undermine the sustainability of Bio waste-based Biogas Energy (BBE) and hence the assessment framework are defined highlighting the associated opportunities and risks. First land use, opportunities and risks are to be taken into account. However since BBE relies on residues such as agro-based residues, it therefore follows that BBE systems do not have stringent land quality requirements. This implies that technically all the land under agricultural production can be deemed to be available for BBE production. Consequently it can be accentuated that BBE production does not compete with agricultural land and avoids conversion of land with high carbon stocks. In addition since bio waste energy relies on bio waste such as agro residues, it suffices to say that there are no inherent land use risks specific to BBE production. The second sustainability issue of major concern is resource use, opportunities and risks. While BBE offers possibilities for improving efficient utilization of raw materials, there are concerns on how to tackle potential risks such as soil organic carbon stocks. Nevertheless, the possibilities for closed loop biomass resource cascade configurations are deemed to sufficiently address the forgoing concerns.
Keywords: Sustainability framework, Bio waste biogas, energy, Kenya.

1. Introduction

Energy including renewable and geologic storages is an essential input to global sustenance and development. The world's energy consumption is estimated to increase exponentially from the current 22 billion kWh yr^{-1} to 53 billion kWh by 2020 (Omer 2008). Such escalating demand could place significant strain on the current energy infrastructure and potentially damage the environment via emission of toxic chemical pollutants, greenhouse gases like CO_2 and other air pollutants (Omer 2008, Wang et al. 2009). These cause climate change and environmental pollution of air, water and land which in turn has a negative impact on the planet as well as the health and living quality of humans. The effects of global warming, diminished natural resources, uneven distribution of energy resources, rising energy prices and hence increased energy demand constitute an energy crisis of global magnitude. The crisis demands an immediate paradigm shift in energy policies with a view of not only revising the existing technologies but paying greater attention to alternative energy sources. Thus, there is a need to identify new technologies as well as alternative renewable and environmental friendly sources of energy. The development of cost-effective renewable energy technologies for energy production is a priority for many private firms, research centres and governments. Availability of secure, affordable, reliable, clean and sustainable energy supply is therefore regarded as one of the key drivers of development and enhancement of the quality of life. To this end, biofuel technology has been identified as quite a promising technology (Cardona and Sanchez 2007, Kondili and Kaldellis 2007) due to its potential of being a significant source of energy. Nevertheless, renewable energy contributes as much as 20% of the global energy supplies worldwide. Over two thirds of this comes from biomass use, mostly in developing countries. While some of the global energy supplies are unsustainable, the potential for energy from sustainable technologies is great. Bio waste energy technologies (BETs) such as bio waste based biogas, bio ethanol and biodiesel are some of the technologies widely regarded as being sustainable.

1.1 Biomass and bio waste energy

Biomass, which comprises any organic matter such as plants and animal waste, is one of the oldest energy resources and raw material known to man and an important contributor to the world economy. The biomass that is produced for any specific application can be referred to as primary resource whereas any biomass without a specific application as well as the residue from primary resources can be broadly regarded as a secondary resource. Bio waste can thus be defined as secondary resource biomass. From this perspective, bio waste can be seen as a biomass by-product without immediate value and whose disposal could incur economic and or environmental cost. Generally biomass is per definition renewable and sustainable if the amount utilised equals the amount that is naturally replenished. Primary biomass such as energy crops is cultivated with a specific purpose in mind, and the conversion technologies that use this biomass are dedicated conversion plants. For example sugarcane is grown for the purpose of producing sugar or ethanol and is therefore a primary source. The residues of sugarcane processing are bio waste and can be either processed separately or mixed up with other bio waste and therefore deemed a secondary source. Use of bio waste as a source of energy thus transforms a negative-value substance, namely waste; into saleable products such as energy and/or compost therefore it is useful in reducing waste, and providing fully renewable energy. Bio waste energy thus facilitates the closing of the biomass production cycle. Other advantages of bio waste energy emanate from the fact that the feedstock source is readily available and does not rely on additional land use or the development of specific cultivation technologies (International Energy Agency 2016). Furthermore, bio waste energy based on agricultural residues offers the opportunity for farmers to profit from biofuel production, which could positively affect rural development, especially in developing countries.

In the recent past a lot of research has emerged worldwide on the utilization of biomass for generation of energy (Kondili and Kaldellis 2007, Sanchez and Cardona 2008). Indeed, biomass in all its forms is researched to account for over 16% of the world's final energy consumption by 2020 and almost 30% of the total global primary energy consumption in 2050 will be covered by regenerative energy sources (Deublein and Steinhauser 2008). Already in developing countries, biomass currently provides over 35% of the final energy consumption (International Energy Agency 2016) and its utilization is expected to increase as a strategy for carbon dioxide reduction. Indeed a lot of efforts have been expended in the studies of biofuel production leading to development of technologies with varying degrees of success. The main challenge has been on the production cost, which is found to be higher than that of fossil fuels. In addition, the cultivation and use of energy crops for energy production may contravene the drive towards food security especially in most developing countries (Deublein and Steinhauser 2008). However, a substantial reduction in the cost of biofuel production can be achieved by addressing the problems associated with raw materials and the utilization of bio waste. Indeed the future of biofuels in most developing countries lies on the identification of non-food plants that can be grown in underutilized land and cascade utilization of the available bio waste such as plant residues. Nevertheless, plant residues are some of the most under exploited resources in most developing countries in spite of the fact that most of these countries' economies are depended on agricultural production. As an example, agro biomass residues such as cotton and sisal waste theoretically have high energy potential primarily owing to their high cellulose content. Besides, there are several conversion options for transforming biomass or bio waste into solid, liquid or gaseous secondary energy carriers (Figure 1.1), these include thermo-chemical transformation via combustion, pyrolysis, liquefaction or gasification; physico-chemical transformation by compression, extraction, transesterification and biochemical transformation via alcoholic fermentation and anaerobic digestion.

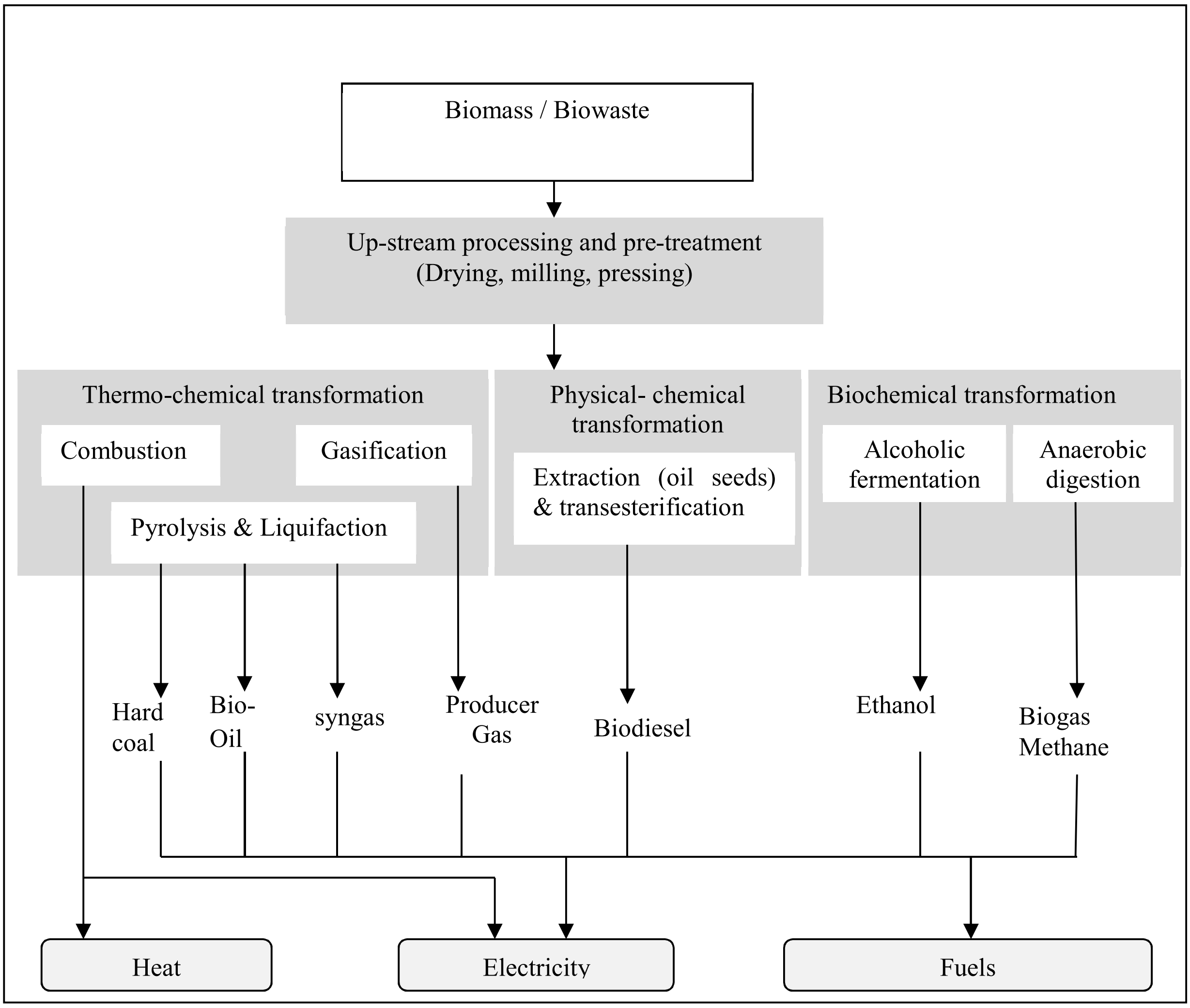

Figure 1.1 Technology options for transforming biomass/bio waste into secondary energy carriers. (Modified from Deublein **(Deublein and Steinhauser 2008)).**

1.1.1 Thermo chemical transformation

The energy stored in biowaste is released when this biomass is combusted. When the requirement is purely thermal, it can be met by using combustion systems and appropriately transferring heat to the required devices. The use of biowaste for energy production can be achieved commercially through boiler and steam turbines though this route is only efficient and economical at large power levels of the order of 5 MW or more. However due to the high capital investment required for large thermal power plants coupled with treatment costs in the range of 50 – 150 €`/tonne (Faaij 2006) and the low bulk density of most biowaste as well as the presence of agrochemical residues especially combustion may not be a viable option for certain biowaste such as cotton waste. Gasification of biomass on the other hand provides means for power generation at lower levels of cost per mega watt comparable to large thermal power plants. During gasification, the solid biomass residues are converted to a gaseous fuel called the producer gas. The producer gas thus generated can be used just like other gaseous fuels such as natural gas, besides, it can also be used for power generation in internal combustion engines or gas turbines. Pyrolysis converts biomass at temperatures around 500°C in the absence of oxygen to solid (hard coal), liquid (bio-oil) and gaseous fractions (Faaij 2006). Liquifaction is another way of converting biomass under high pressure into raw intermediate liquids (bio-oils). To date, pyrolysis and liquefaction are still quite expensive hence less well developed and the actual market implementation is so far negligible.

1.1.2 Physical-chemical transformation

Certain types of biowaste such as cotton gin waste and coffee berry residues contain oily seed fragments. When such biowaste is crushed and pressed, the resulting oil can be processed through transesterification to produce a high-quality biodiesel that can be used in a standard diesel car. The residue (press cake) can also be processed and used as biomass feedstock to power electricity plants or used as feedstock for biogas production while the resultant digestate can be used as fertilizer. Nevertheless, the biodiesel industry is largely depended on dedicated energy crops. For instance, biodiesel production in Europe is largely dependent on rapeseed even though the use of waste vegetable oil is gaining prominence. On the other hand, in Africa biodiesel production from non-edible oil seeds such as jatropha curcas is gaining immense attention.

1.1.3 *Biochemical transformation*

Biochemical transformation via alcoholic fermentation and anaerobic digestion offers a very attractive route to utilize diverse categories of biomass and biowaste for meeting energy needs as well as contributing to resource and environmental conservation. Alcoholic fermentation and anaerobic digestion of biowaste into ethanol and biogas respectively can serve as a vital tool in closing the biomass value chain thus contributing to national development.

1.2 The role of biochemical transformation in a cascaded utilization of biomass.

Utilization of the potential presented by biomass and biowaste via a cascade system for biogas energy production and the subsequent use of the digestate as green manure can provide multiple environmental (Satyanarayan and Murkute 2008) and socio-economic benefits to the users and the community thus alleviating poverty. Indeed a simple yet all inclusive strategy for promoting the usage of biowaste might be the closed loop cascaded system (Figure 1.2). Bioconversion processes such as ethanol and biogas production can be employed as means of waste valorisation in energy production systems. The production of ethanol from biowaste can improve energy security and decrease pollution. Ethanol is an excellent transportation fuel and when blended with gasoline it leads to reduced gasoline use, thus lowering the need for fossil fuels. Besides the ethanol–gasoline blend has a better performance since ethanol provides oxygen for the fuel resulting in a more complete combustion with a low atmospheric photochemical reactivity. The ability of the biowaste derived glucose to be fermented by yeasts into bioethanol does not only address the issue of renewable energy but could also serve to control the accumulation and associated environmental problems due to biowaste.

Two main approaches i.e., phased and direct microbial conversion, have been examined for the hydrolysis of waste cellulose into glucose and the successive fermentation into bioethanol and other bioproducts (van Wyk 2001). The phased microbial conversion makes use of separate hydrolysis and fermentation processes whereby cellulase is added to pretreated biowaste resulting in the formation of glucose from the cellulose fraction after which yeast is added to ferment glucose into ethanol (Cardona and Sanchez 2007). With the direct microbial conversion, the microorganisms simultaneously produce cellulase, hydrolyze cellulose and ferment glucose into ethanol while at the same time, co-fermentation converts the hemicellulose sugars into bioethanol (Sanchez and Cardona 2008, Stenberg et al. 2000). Over the years there have been substantial advances in enzyme-based technology for ethanol production.

Biogas on the other hand is produced through biomethanation process, which is a biological transformation through which organic matter is degraded to methane and carbon dioxide. The biomethanation process consists of a series of discrete reactions catalysed by a consortium of metabolic groups of different bacterial species through which organic matter is converted to the main products of methane and carbon dioxide (Ranalli 2007, Yadvika et al. 2004). Indeed most biomass based upgrading and production processes release organic by-products and wastes thus biomethanation can be advantageously implemented into these technologies as a energy production, fertilizer recovery and waste stabilization process. In addition, biomethanation could eventually contribute a significant portion of the country's lighting requirements especially in the rural areas.

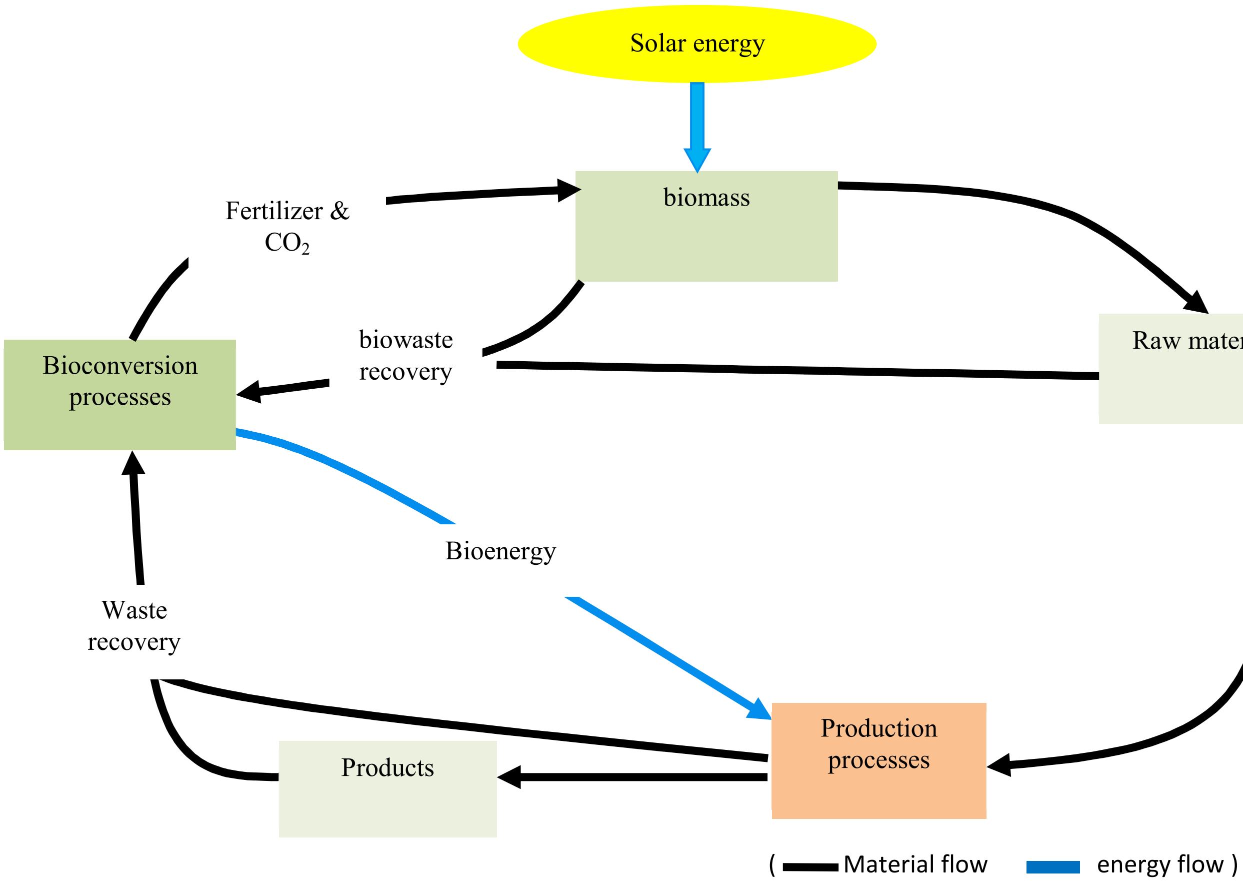

Figure 1.2: Cascaded system for the utilization biomass and biowaste, showing the role of bioconversion process in closing the loop.

The bio-energy produced through biomethanation of agro-biowaste such as sisal and cotton can supplement the energy needs of the textile production processes while the energy savings can be used to enhance the profit of the farmers. Besides, the subsequent use of the digestate as green manure can provide multiple environmental and socio-economic benefits to the users and the community thus contributing to poverty alleviation. Moreover, realization of high-efficient bioconversion processes at places where the biowaste can be gathered and or translocated and where the 'green' products can be sold to a cluster of end users can be a vital key towards meeting the longer-term policy goals in most developing countries.

2 The Sustainability Concept

Sustainability and sustainable development are broad concepts that have continued to attract increased attention within the public and private sector hence eliciting wide ranging discussions and debate over the last two decades. However, given their ubiquitous use and popularity, the lack of a concrete definition of 'sustainable' may appear rather surprising. Nevertheless, several definitions have been put forth (Heijungs et al. 2010, Simon and Morse 1999, Winterton 2003) including the most quoted definition after the sustainable development report of the World Commission on Environment and Development (World Commission on Environment and Development 1987), commonly referred to as the Brundtland report of 1987. "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". This definition is however open to various interpretations largely depending on how the needs of the present and future generations as well as the earth's carrying capacity to supply them are defined. Sustainable development is thus a very dominant theme in the global development interventions. The main catalyst for this dominance in recent years can be traced to the 1992 Rio de Janeiro Earth Summit that put forth a set of action points for sustainable development, collectively referred to as Agenda 21 (Simon and Morse 1999). In its broadest sense, the sustainable component of the sustainable development paradigm implies that whatever is done now should not harm future generations.

The sustainability concept has been explored further, and today, it is conceived as having three dimensions: the social-cultural, the economical and environmental dimension (Finkbeiner et al. 2010, Mauerhofer 2008). The social-cultural sustainability aims at preserving the stability of social and cultural systems whereas the economic view of sustainability aims at attaining maximum economic benefits at minimum cost while at least maintaining the assets on which the benefits are based. On the other hand, sustainability in the ecological sense means that the natural basis for life, that is the ecosystem, ought to be maintained therefore the ecosphere should not be exposed to an intolerable load. Nevertheless the conundrum is that the ecosystem, which is the basis of humanity's existence, needs to be maintained in order to fulfil its functions in the future. However, the conundrum presents a concise view of sustainability: ***sustainability is a technical balance between the present and future interests***. Sustainability can consequently be seen as the final target, that is, a balance of social and economic activities and the environment (Hofman and Li 2009) whereas sustainable development is the means of reaching the anticipated target. Therefore, to attain sustainable development in its entirety, all three dimensions of sustainability have to be taken into account. The interaction of the three dimensions and some of the preferred characteristics necessary to bring about sustainability is often viewed in terms of the "3 P's" of sustainable development: People, Profit and Planet as introduced by Elkington (Elkington 1997). This presentation underscores the need to integrate the sustainability dimensions and is presented in Figure 2. Coincidentally, the technicality behind and the result of, the integration of the three sustainability dimensions brings forth another aspect of sustainable development which has come to be referred to as the technical aspect (Wang et al. 2009). Nonetheless, concepts and evaluation techniques taking care of all the aspects simultaneously are not available.

Figure 2: The 3 P's (People, Planet and Profit) and preferred characteristics for sustainable development.

There are many factors that can contribute to achieving sustainable development. One of the most important within a society is the sustainable supply and an effective and efficient utilization of renewable energy resources (Dincer 2000). However, because renewable energy resources are stochastic and geographically diffuse, their ability to sustainably match demand is determined by adoption of either of the two approaches (Omer 2008): first, the utilization of a capture area not greater than that occupied by the community to be supplied and secondly, the reduction of the community's energy demands to a level commensurate with the locally available renewable resources. Sustainable development hence requires, among other things, the greater understanding of how renewable energy interrelates with the physical, natural and living world through studies of the chemistry and life cycle of substances, materials and organisms, their form, properties and behaviour as well as the interactions thereof. Such understanding is critical in solving the Trilemma (Nitta and Yoda 1995), that is, meeting the societal needs of a growing world population while minimising deleterious effects on the environment. Hence, for instance, a sustainable energy sector has a balance of energy production and consumption and has no, or minimal, negative impact on the environment, but presents a conducive opportunity for a country to employ its social and economic activities.

3 The multi-criteria sustainability framework

The multi criteria sustainability framework (MCSF) is a format for integrated sustainability evaluation that seeks to account for complex and evolving biophysical and socio-economic systems by addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives. Compared to the conventional single criteria approach that seeks to identify the most efficient options at a low cost, the MCSF seeks to obtain an integrated result by employing multiple criteria or attributes. The MCSF for an energy system therefore ought to facilitate evaluation of the extend in which the system is deemed to be economically viable (economic sustainability), technically efficient (technical sustainability), environmentally bearable (environmental sustainability) and socially equitable (social sustainability). Hence, four main sustainability aspects do suffice namely economic, technical, environmental and social dimensions (Afgan et al. 2000, Finkbeiner et al. 2010, Mauerhofer 2008). Congruent to the sustainability dimensions are impact categories and the respective indicators.

Indicators have been widely employed by biologists for many years to gauge ecosystem health hence they are widely regarded as the core element in operationalizing sustainability. However, unlike most biological systems, sustainability incorporates many more dimensions (Mauerhofer 2008) thus a number of indicators are almost certainly required. Furthermore, due to the amount of sustainability criteria and indicators, their selection and prioritization is of main importance. The problem then becomes how many and which indicators to use? Clearly one cannot employ every sustainability indicator (SI) that may potentially be available (Nzila et al. 2012) hence an element of simplification while concurrently maximising unique and relevant information is essential. However, given the political character of sustainability definitions, building consensus on the selection, prioritisation and simplification of such indicators is a complex task. Nevertheless, the following principles do suffice and are generally obeyed (Simon and Morse 1999):

(1) Systemic principle: The scope of the indicators should be relevant and should cover the diversity of issues (environmental, social and economic) with minimal overlap.
(2) Consistency principle: The indicator should be consistent with the criteria objective, reliable and easy to contextualise without limiting the capacity to draw conclusions.
(3) Measurability principle: The indicator should be measurable in quantitative value or qualitatively expressed.
(4) Independency principle: The indicator should reflect the performance of alternatives from different aspects and should not have any inclusivity relationship at the same criteria level.

Other general requirements for indicator selection are reliability, relevance, completeness, non-redundant and independence of preferences. Nevertheless, sustainability indicators have been a struggle of several public and private organisations with the focus being to produce a single definitive set of indicators (Dewulf and Van Langenhove 2005). However the adept aggregation of indicators is not only complex but suffers from the inherent disadvantage of loss of detail due to the loss of identity of the individual indicators in the final result. In this dissertation, the formulated MCSF departs from the classical approach by attempting to take into account the environmental, socio-economic and technical aspects of sustainability and retaining the identity of the indicators in the final integrated result. The framework proposes nine impact criteria categories and the respective indicators as presented in Figure 3. While the criteria chosen are applicable to a wider setting where environmental, technical and socio-economic considerations are required, the corresponding indicators and units have been defined with specific focus to biogas production systems.

In Table 3, the framework is further elaborated showing the operationalization as progressively defined by the objectives and the proposed impact criteria indicators and the corresponding indicator units. The following sections summarise the MCSF methodology with regard to the environmental aspect, the technical aspect and the socio-economic aspect.

Table 3: Definition of sustainability objectives and impact criteria indicators applied in the MCSF for the assessment of biogas production

Sustainability Aspect/dimension	Objective	Specific objective	Impact criteria category	Indicator	Definition	Indicator Units
Environmental	Maximise environmental performance	Minimise environmental pollution	Global warming reduction	GHG balance	Green House Gas emission saving as a result of replacing fossil fuel (kerosene) with biogas.	$kgCO_2eq/Nm^3$
		Minimise energy demand	Energy demand	Cumulative energy demand	The amount of energy consumed to produce a unit volume of biogas	MJ/Nm^3
		Minimise resource loses and depletion	Resource depletion	Exergy equivalent	The amount of energy that is available to be used per unit of production	MJ_{ex}/Nm^3
Technical	Maximise technical viability	Maximise useful energy	Energy breeding	Energy balance	The ratio of output energy to the input energy	MJ_{out}/MJ_{in}
		Minimise the period needed to recoup invested energy	Energy payback	Energy payback period	A measure of the time period over which the energy generated equals the expended energy	Years or months
		Maximise performance	Reliability	Operational reliability	Capacity of the system to perform as designed without need for extensive refurbishment	%
Socio-economic	Maximise socio-economic benefits	Maximise savings	Energy autonomy	Fossil energy replacement saving	A measure of savings arising from the substituted of fossil energy resources per unit of production	$/Nm^3
		Maximise economic viability	Total investment	Total capital investment cost	A measure of the valorisation of investment per unit of production	$/Nm^3
		Maximise labour productivity	Labour	Direct labour cost	A measure of the cost of labour per unit of production	$/Nm^3

3.1 Environmental sustainability aspect

The main objective with regard to the environmental sustainability aspect is the maximisation of environmental performance. When biogas systems are compared to other bio energy systems such as biodiesel and bioethanol production systems, they are normally found to lead to environmental improvements in terms of lower emissions to soil and water and the potential recovery of nutrients (Berglund and Borjesson 2006). However, when different biogas systems are compared together factoring in different infrastructures of production, the environmental impact of the background processes suffice. The direct implication of extending the system beyond the biogas production facility is that the requirement to account for emissions of the background processes such as the production, handling and transport of (bulk) raw materials. Sources of GHG emissions in the background processes are mainly from the use of fossil fuels, fertilizers and land use change. In this framework, three specific objectives pertaining to minimisation of environmental pollution, energy demand and resource depletion are defined (Table 3.0). The assessment of the environmental performance is done by means of the Life Cycle Sustainability Assessment (LCSA) which represents the state of the art in science and application based on the ISO 14040 and 14044 environmental standards (Arvanitoyannis 2008).

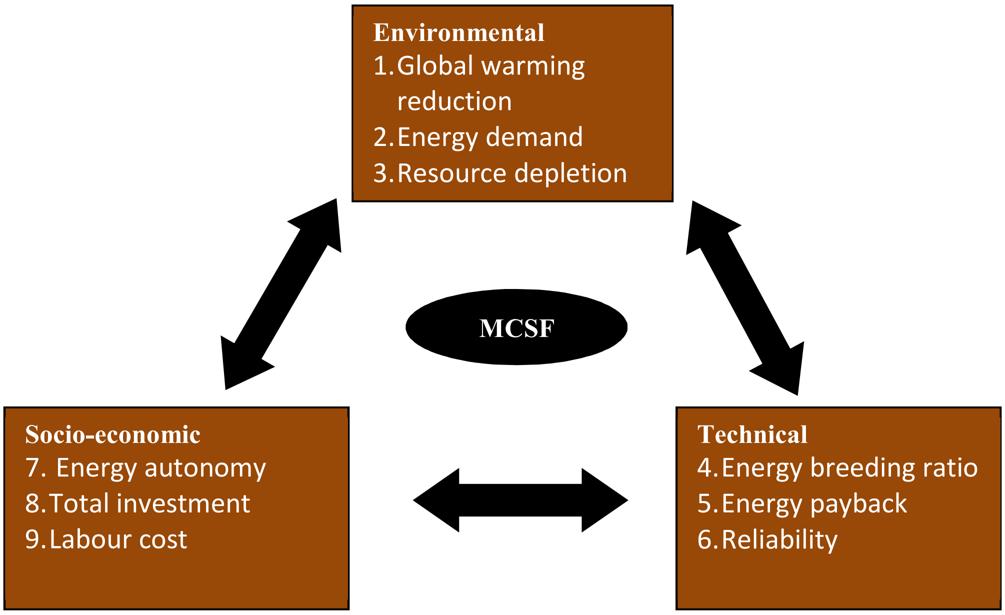

Figure 3: Sustainability dimensions and criteria applied in the MCSF

3.2 Technical sustainability aspect

The main objective with regard to the technical sustainability aspect was to maximise technical viability while the specific objectives related to maximisation of useful energy and performance and minimisation of the period needed to recoup the invested energy. Comparison of different biogas systems has shown that there exist differences in energy efficiency for different installations thereby causing differences in performance (Börjesson and Berglund 2007). In this regard, the objective on maximising useful energy seeks to determine the energy balance for the different biogas systems considering the respective output and the input energy. The objective pertaining to energy payback seeks to establish the time span over which the invested energy is recouped for the different biogas systems. On the other hand, the objective on maximising performance seeks to compare the different biogas systems in terms of their respective reliability.

3.3 Socio-economic sustainability aspect

Technology is arguably one of the key drivers of socio-economic advancement since people are the creators and key beneficiaries of the ensuing benefits. The improvement of living conditions and the enhancement of socio-economic structures are key goals for biogas initiatives (Nzila et al. 2010). The main objective pertaining to the socio-economic aspect was therefore to maximise socio-economic benefits whereas the specific objectives are chosen with a view to maximise savings, economic viability and labour productivity. The characterisation of the different socio-economic impact categories for the different biogas systems seeks to quantify the savings arising due to the replacement of fossil fuel with biogas, as well as the valorisation of capital and determination of labour productivity.

4 Operationalizing the MCSF for biogas production

The operationalization of the MCSF to compare different alternatives for biogas production is graphically illustrated in Figure 4.0. The inventory data, commonly in distinct measurements but usually presented per functional unit, is processed for each indicator in accordance with the LCSA approach and chosen characterisation factors to yield the corresponding impact category scores. The three impact category scores for each sustainability dimension are presented separately and comparison for the different alternatives under investigation is performed for each dimension. The three dimensional scores are then dimensionally normalised so as to be presented in a radial unit spider-gram for an integrated comparison of the three alternatives for biogas production.

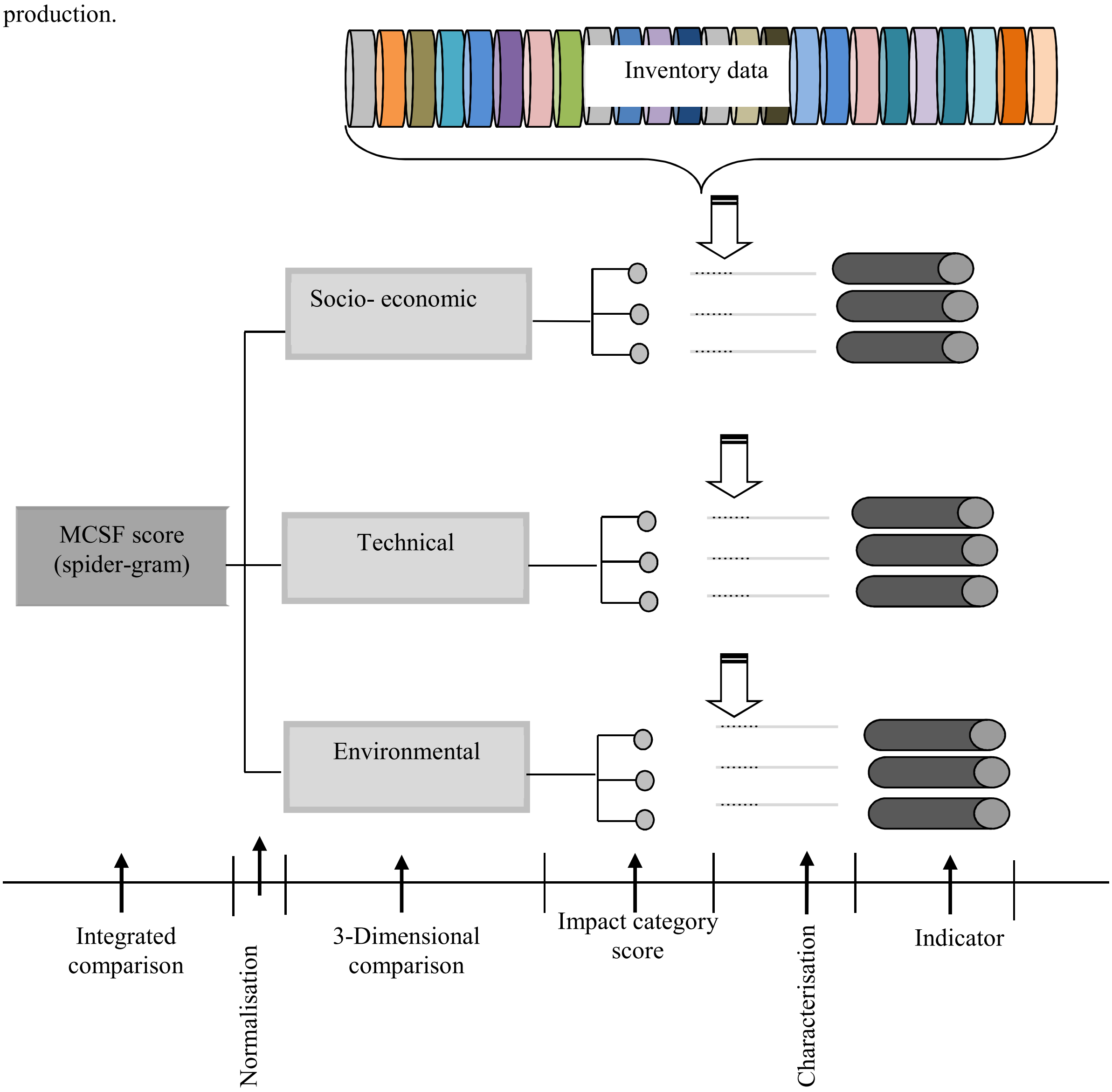

Figure 4.0: MCSF evaluation scheme addressing the characterisation of impacts and comparison at each dimension level as well as normalisation and the eventual integrated comparison.

All the impact criteria in the spider-gram are given equal prominence and scaled with increasing level of suitability from zero to one. The total spider-gram area occupied by the different alternatives (or length of the nodes) denotes their suitability with respect to the impact criteria under consideration. Characterisation of the impact criteria categories based on LCA and are summarised in Table 4.0 while the inherent calculation formulae are presented in the appendix.

Table 4.0: Characterisation factors for operationalizing the MCSF

Indicator	Characterisation factor	Units
GHG balance	$GHG\ balance = GHG_{replaced\ fossil} - GHG_{biogas\ prod.}$	kg CO_2 eq/Nm^3
Cumulative energy demand	$CEENE_j = \sum_{i=1}^{184}(X_i * a_{ij})$	MJ_{ex}/Nm^3
Exergy equivalent	$CED = \sum_j X_j * n_j$	MJ/Nm^3
Energy balance	$Energy_{out} / Energy_{in}$	MJ/Nm^3
Energy payback period	$\frac{\sum Energy_{in}\ (MJ)}{Energy_{out/yr}\ (MJ/yr)}$	Years
Operational reliability	$\frac{\sum Digesters_{faultless}}{\sum Digesters} x100\%$	%
Fossil energy replacement saving	$\left\{\frac{Energy_{biogas}\ (MJ/m^3)}{Energy_{fossil}\ (MJ/kg)} - Q_{fossil}\ (kg/Nm^3)\right\} * P_{fossil}\ (\$/kg)$	\$/ Nm^3
Total capital investment cost	$Cost_{invest}\ (\$) / V_{biogas}\ (Nm^3)$	\$/ Nm^3
Direct labour cost	$Cost_{labour}\ (\$) / V_{biogas}\ (Nm^3)$	\$/ Nm^3

4.1 Operationalizing the environmental sustainability dimension to assess the impact of bio waste valorisation to the environmental profile of African textiles.

The environmental criterion in the sustainability framework is built upon the recognition of two philosophies pertaining to the way people interact with their natural environment. First, is the fact that natural resources are finite therefore they need to be used wisely. Second, is the notion that the use of resources by humans can pose negative consequences to the environment such as pollution that ought to be avoided or at least mitigated. Following these two notions and pursuant to the conclusion from the second law of thermodynamics (Atkins 1984, Winterton 2003) that there is no such a thing as a waste-less process, the objective of maximising environmental performance in the textile sector can be structured considering the added value of bio waste valorisation to the environmental profile of the textiles. This approach has been further elaborated in Nzila et al (2016) where the results unveil interesting insight for sustainable management and branding of the African textiles.

4.2 Bio waste-based biogas energy specific sustainability issues

Bio waste-based biogas energy (BBE) has various unique features that can significantly reduce some of the sustainability problems faced by many terrestrial biofuel sources. For example no direct/indirect land use changes or competition for agricultural land, besides, BBE offers an opportunity for fertilizer production instead of consumption. Nevertheless, integrating the full potential of all these benefits influences other choices within the BBE concept. In addition, choosing the most environmentally, economically and socially sustainable approach is quite complex. Nonetheless, some important risks and opportunities to be considered are discussed below.

4.2.1 Land use: opportunities and risks

Direct land use changes (LUC) are caused when new areas or virgin land such as forest areas or degraded land are taken into production to directly cover the additional energy feedstock demand. On the other hand an indirect land use change (ILUC) is caused when existing agricultural land is used to cover the feedstock demand of additional bio fuel production. This will indirectly cause an expansion of the land use for biomass production to the new areas when the previous users of the feedstock, such as food markets, do not scale down their feedstock demand. Both LUC and ILUC can have positive and negative consequences on aspects such as biodiversity, carbon stocks and livelihoods (Simon and Morse 1999). Nevertheless, since BBE relies on residues such as agro-based residues, it therefore follows that BBE systems do not have stringent land quality requirements. Technically all the land under agricultural production can be deemed to be available for BBE production. Consequently there is an enormous amount of land suitable for BBE production that does not compete with agricultural land and avoids conversion of land with high carbon stocks. Generally since bio waste energy relies on bio waste such as agro residues, it suffices to say that there are no inherent land use risks specific to BBE production.

4.2.2 Resource cascading: opportunities and risks

Resource cascading, which implies the sequential exploitation of the full potential of a resource during its use (Clift 1995), is one of the key ways of improving efficient utilization of raw materials. Biomass cascading for instance via BBE production is thus an important concept to consider when striving for efficient biomass utilization. BBE thus offers one of the possibilities for exploiting valuable biowaste characteristics. Indeed current conditions of residue availability and the associated environmental nuisances, as well as the demands from the climate change agenda and the global transition towards a biobased economy are triggering new opportunities and frontiers for BBE (Nzila et al. 2010, Verstraete et al. 2005). The flexibility and simplicity of BBE thus renders it to be able to increase its contribution to economical and environmental sustainability of the entire biomass chain through waste reduction and production of extra energy and bio fertilizer for soil amendment in a closed loop biomass resource cascade configuration (Figure 4.2.2).

Several examples demonstrating the contribution of BBE to biomass cascades have been shown. Van Haandel (van Haandel 2005) demonstrated the digestion of vinasse and bagasse resulting from the production of ethanol from sugarcane in Brazil where 8,750 kWh are produced in addition to the 5,000 litres ethanol produced from the original 65 – 75 ton wet sugarcane. Similarly in another study (Clarke et al. 2008) it was demonstrated that there are no technical barriers to cascading the utilization of banana biomass at a commercial scale in Australia. In this study it was shown that 1 ton of banana waste per day can generate 7.5 kW of electricity, enough to supply six to eight houses. Moreover, the added value of BBE to a grass biorefinery concept has also been demonstrated in Switzerland (Baier and Delavy 2005). In this particular case BBE adds value to the biomass chain by generating 500 kWh per ton grass in addition to the 0.4-tonne fibres and 0.12 tonne proteins originally produced from the initial ton of biomass. A similar study in Kenya (Nzila Charles et al. 2009) obtained that if 50% of the sisal and cotton residue can be harnessed for bioconversion into energy, about 94,000 MW of electricity and 141,000 MW of thermal energy can be generated.

Most technological research in the field of bioenergy focuses mostly on one stage of the process and the inner system possibilities for optimization of the process efficiency. However research is needed for the optimization of the full chain considering demands of the expanded boundary of the outer system as envisaged in figure 4.2.2.

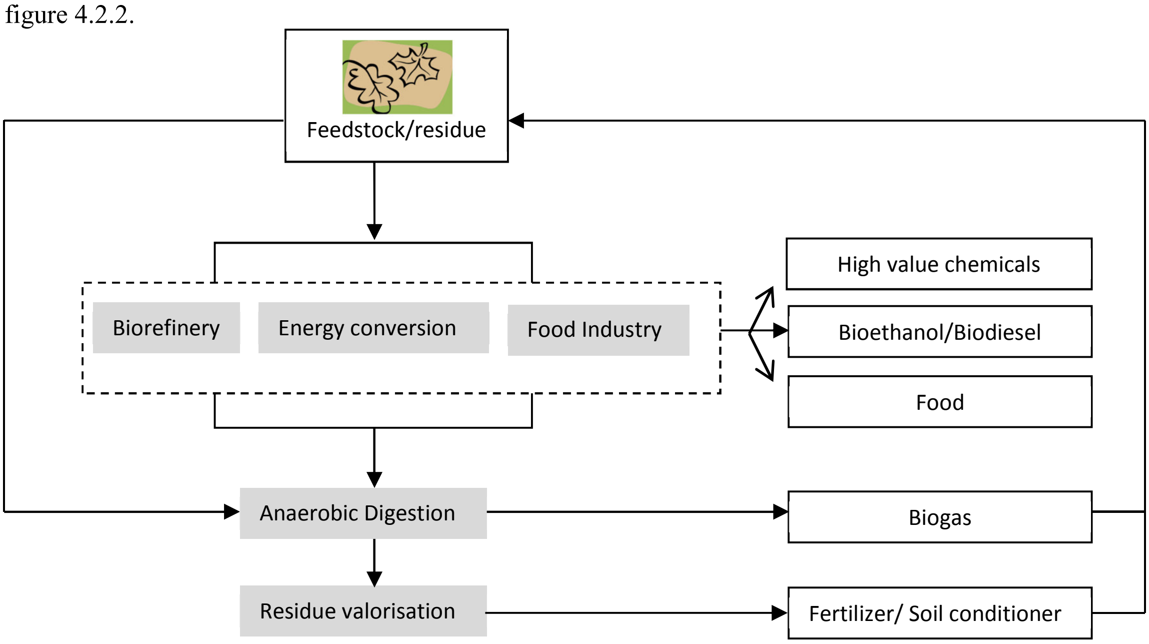

Figure 4.2.2: Possibilities for closed loop biomass resource cascade configurations having anaerobic digestion as a key element for BBE.

Hence the question that suffices is how to tackle any potential risks as well as how the expanded boundaries and resource cascade conditions influence the role that BBE can play in the different biomass chains. One of the possible problems of BBE production is associated with humus formation from the agro residues. For instance when the BBE production systems are centralised, it then necessitates transportation of the BBE feedstock from the agricultural fields to the BBE facilities. Consequently concerns are that such translocation of biowaste may have a negative effect on soil quality, especially on soil organic carbon stocks (Brandão et al. 2010). Indeed if the digestate slurry is not transported back to the fields then the soils could be deprived of the vital constituents for humus formation.

4.3 Kenya as a case study area and biogas as a case study bio energy carrier

The possibility of creating energy and other products in a competitive way out of biomass as well as bio waste might improve the economic conditions of vast population in developed and developing countries (Nielsen et al. 2004). Tropical developing countries especially in Africa are perceived as having good bioenergy production potential (Nzila et al. 2010) as they possess large tracts of land, good agricultural production conditions in terms of sun hours, rainfall, low temperature fluctuations and cheaper production costs as compared to Europe (Faaij 2006). However concerns are in place as pertains to the low utilization of bio waste for energy production.

Kenya can be regarded as a country exemplifying such a panorama, having a wide range of opportunities for the utilization of biomass and bio waste besides emerging concerns due to the rapid global developments in bioenergy production. Agriculture is a key sector of Kenya's economy, contributing about 25% of the Gross Domestic Product (GDP) and providing employment to an estimated 70% of the labour force. According to the Kenya Integrated Household Budget Survey report (Nassiuma 2007), 68.8% of all households in Kenya are engaged in crop farming activities. In the rural areas, this proportion stands at 85.4%. Farming is practiced on an estimated 12.3 million acres out of a total area of about 146.5 million acres. However, irrigation farming is practiced only in 6% of all agricultural parcels. Furthermore, 66.0% of the households keep at least one type of livestock with poultry and cattle being the predominant livestock. 67% of the households rear chicken while 64% of the households rear cattle. Other livestock types reared include goats, sheep, pigs, camel and donkeys. Nationally, the country's energy matrix show that 68.3% of all households use firewood as cooking fuel and over 80% of rural households rely on firewood for cooking compared to 10% of the households in urban areas. The percentage of households using electricity for cooking was reported to be 0.6% whereas the usage of biogas was insignificant, recorded at below 0.1% (Table 4.3). On the other hand, kerosene is the major source of lighting fuel in majority of households (76.4%). One of the most important constraints facing biogas technology dissemination in the country is inadequate feedstock for biogas production (Nzila et al. 2010). The incorporation of BBE into Kenya's energy matrix could thus deliver various benefits like the delivery of valuable biogas for farmers to use in different applications such as cooking, heating and lighting. The reincorporation of nutrients and residual carbon into the land is another additional benefit. The Kenya case can serve as a model case that can further be extrapolated and applied to other East African countries.

Table 4.3: Energy use (%) for cooking and lighting in Rural and urban areas of Kenya

Source of energy	Rural		Urban		National	
	Cooking	Lighting	Cooking	Lighting	Cooking	Lighting
Electricity	0.2	3.9	1.8	51	0.6	15.6
Kerosene	2.7	86.4	44.6	46.3	13.2	76.4
Fuelwood	87.7	5.8	10	0.5	68.3	4.5
Charcoal	7.7	-	30.2	-	13.3	-
Solar	0.0	2.0	0.0	0.7	0.0	1.6
LPG	0.7	0.2	11.9	0.2	3.5	0.2
Biogas	0.0	0.0	0.1	0.0	0.0	0.0

Source: Kenya Integrated Household Budget Survey, 2007 (Nassiuma 2007)

5 Conclusion and Recommendations

An overview and development of the sustainability assessment framework for the assessment of bio waste based biogas energy has been presented in this work. The key innovative aspects of the proposed framework are the development of a multi dimensional assessment system with a typology of multi criteria indicators relevant for biogas energy. In addition two main sustainability issues that could potentially undermine the sustainability of Bio waste-based Biogas Energy (BBE) and hence the assessment framework have been defined while highlighting the associated opportunities and risks. First land use, opportunities and risks need to be taken into account. However it can be concluded that since BBE relies on residues such as agro-based residues, it therefore follows that BBE systems do not have stringent land quality requirements. This implies that technically all the land under agricultural production can be deemed to be available for BBE production. Consequently it can be stressed that BBE production does not compete with agricultural land and avoids conversion of land with high carbon stocks. In addition since bio waste energy relies on bio waste such as agro residues, it suffices to say that there are no inherent land use risks specific to BBE production. The second sustainability issue of major concern that has been addressed is resource use, opportunities and risks. In this regard it can be concluded that while BBE offers possibilities for improving efficient utilization of raw materials, there are concerns on how to tackle potential risks such as soil organic carbon stocks. Nevertheless, it can be recommended that the possibilities for closed loop biomass resource cascade configurations are deemed to sufficient to address the forgoing concerns.

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7 Appendix:

Calculations in the Multi Criteria Sustainability Assessment framework.

Cumulative exergy extracted from the natural environment for a product *j* ($CEENE_j$), MJ_{ex}

$$CEENE_j = \sum_{i=1}^{184}(X_i * a_{ij}) \quad \text{(eq 1)}$$

Where:

X_i = characterisation factor of the i^{th} reference flow (MJ_{ex}/kg, MJ_{ex}/MJ, MJ_{ex}/Nm^3, MJ_{ex}/m^2.a)

a_{ij} = amount from reference flow *i* (kg, MJ, Nm^3, m^2.a) necessary to obtain product *j*.

Cumulative energy demand (*CED*), MJ

$$CED = \sum_j X_j * a_j \quad \text{(eq 2)}$$

Where:

X_j = characterisation factor of resource *j* (MJeq/kg, MJeq/m^3, MJeq /m^2a),

a_j =amount of resource *j* (kg, Nm^3, m^2.a per functional unit)

Green House Gas (GHG) Saving

$$\text{GHG saving} = GHG_{\text{replaced fossil}}\ (\text{kg } CO_{2\,eq}/m^3) - GHG_{\text{biogas prod}}\ (\text{kg } CO_{2\,eq}/m^3) \quad \text{(eq 3)}$$

Where:

$GHG_{\text{replaced fossil}}$ = CDE_{fossil} (kg $CO_{2\,eq}$ /kg $_{\text{fossil}}$) * FER (kg/m^3)

$GHG_{\text{biogas prod.}}$ = $\sum_j X_j * m_j$

$GHG_{\text{replaced fossil}}$ = Green house gas potential for the fossil fuel replaced by biogas (kg CO_2eq/Nm^3 $_{\text{biogas}}$)

$GHG_{\text{biogas prod}}$ = Green house gas emitted due to biogas production (kg CO_2eq/Nm^3 $_{\text{biogas}}$)

CDE_{fossil} = carbon dioxide equivalent for fossil fuel (kg CO_2eq/kg $_{\text{fossil}}$)

X_j =characterisation factor of emission *j* (kg CO_2 eq/kg)

m_j =mass of emission *j* (kg/ Nm^3 $_{\text{biogas}}$)

Energy breeding ratio (EBR)

$$EBR = \frac{output\ energy\ (MJ/m3)}{input\ energy\ (MJ/m3)} \quad \text{(eq 4)}$$

Where:

- Output energy is the energy content of biogas per unit volume
- Input energy is the energy expended to produce the biogas (cumulative energy demand) per unit volume.

Energy payback period (EPP), years

$$EPP = \frac{total\ energy\ input\ (MJ)}{annual\ energy\ output\ (MJ/yr)} \quad \text{(eq 5)}$$

Where:

- Total energy input (MJ) = energy demand (MJ/m^3) * total volume of biogas produced (m^3)
- annual energy output $\left(\frac{\text{MJ}}{\text{yr}}\right) = \frac{\text{total biogas output } (m^3) * \text{biogas energy content } (MJ/m^3)}{20\ yrs}$

Reliability (Rel.), %

$$\text{Rel. } (\%) = \frac{\sum digesters\ without\ need\ for\ extensive\ refurbishment}{\sum digesters} * 100\% \quad \text{(eq 6)}$$

Total investment cost (TIC), $

$$\textbf{TIC} = \frac{construction\ cost\ (\$) + direct\ labour\ cost\ (\$)}{total\ biogas\ production\ (m3)} \qquad \text{(eq 7)}$$

Where:

- Construction cost = cost incurred ($) in the construction of the respective digester
- Direct labour cost = labour input (man days) * minimum daily wage ($/day)

Fossil Energy Replacement Savings (FERS), $/ Nm^3

$$\textbf{FERS}\ (\$/\ Nm^3) = \left\{\frac{E_{biogas}\ (MJ/m^3)}{E_{fossil}\ (MJ/kg)} - Q_{fossil}\ (kg/Nm^3)\right\} * P_{fossil}\ (\$/kg) \qquad \text{(eq 8)}$$

Where:

E_{biogas} = Biogas energy content (MJ/Nm^3) = 35.8 MJ/Nm^3 (or 9.845 MJ/Nm^3 considering 50% CH_4 and 55% standard biogas stove efficiency)

E_{fossil} = Fossil resource energy content (MJ/kg)

Q_{fossil} = fossil resource used during biogas production (kg/Nm^3)

$= \text{CED non ren.}\ (MJ/m^3)\ x \frac{\delta_{fossil}\ (kg/L)}{G_{fossil}\ (MJ/L)}$

δ_{fossil} =density of fossil fuel (density of kerosene = 0.81kg/l)

G_{fossil} = energy content of fossil fuel (LHV of kerosene) = 37.7 MJ/l (or 18.85 MJ/L considering 50% standard kerosene stove efficiency)

P_{fossil} = Price of fossil resource ($/kg)

Labour Cost (LC) per unit volume of biogas, $/m^3

$$\textbf{LC}\ (\$/m^3) = \frac{\text{Direct labour demand (man-days) x daily wage (\$/man-day)}}{total\ biogas\ production\ (m^3)} \qquad \text{(eq 9)}$$

Where:

The daily wage is based on the average minimum wage consideration in the country