Techno-economical analysis of the benefits of anaerobic digestion at a rural sisal processing industry in Tanzania

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Abstract

The low electrification rates and lack of access to energy services are some of the main challenges of the Tanzanian energy system. However, increasing access to power and other energy services would lead to an increase in the energy demand, which the Tanzanian energy system will not be able to meet. Therefore, new solutions are needed to increase access to modern and affordable energy services that facilitate economic and social development, but in a way that is also sustainable. One promising solution seems to be the use of the abundant agricultural residues to produce energy, which could be particularly relevant for rural areas without access to the national grid.

Further, the Tanzanian sisal industry has a challenge in addressing the emissions from sisal processing. Each year, the national industry produces approximately one million ton of Sisal Decortication Residue (SDR), causing local eutrophication as well as emissions of methane, a potent greenhouse gas.

The solution under study in this thesis is the potential use of the residue generated at a sisal estate in the region of Tanga (Tanzania), to generate biogas, which could potentially produce electricity and heat when fed into a CHP unit. The AD process also reduces the negative environmental impact of the waste. Given the substantial amounts of sisal waste produced at the estate every day, the project aims at providing a solution that will benefit the owner of the estate, the environment and the local communities. It was found that the potential for biogas production is close to 1,200,000 m³ per year. In a CHP unit, this amount of gas would produce around 2,340 MWh of electricity and over 4,160 MWh of heat per year.

The different potential applications for the biogas and products are presented and analysed in the local context. The results of the study suggest that the solution that would provide higher benefits from an economic, social, and environmental perspective is to supply part of the biogas to the surrounding villages for its use as a cooking fuel and fed the remaining electricity into the national grid. For this application it was found that the NPV of the project at the end of its lifetime is close to 1,580,000 USD, and the investment would be recovered in less than 9 years. At the same time, the use of biogas as cooking fuel would significantly benefit the households and the environment, by reducing the serious health and environmental problems derived from the processing of traditional biomass resources.

Keywords

Sustainable development; Tanzania; rural electrification; sisal; CHP; anaerobic digestion; biogas
Sammanfattning

Bristande tillgång till energitjänster är en av de största utmaningarna för energisystemet i Tanzania. Men förbättrad tillgång till energitjänster kommer att leda till en snabb ökning av energibehov i landet, som det tanzaniska energisystemet inte kan hantera. En möjlig lösning kan vara att använda de rikliga jordbruksavfall för energiändamål, särskilt i landsbygdsområdena som saknar tillträde till det nationella elnätet.

Denna rapport studerar möjligheterna att använda avfallet från produktion av sisalfiber (vanligtvis kallade *Sisal Decortication Residue*, SDR) som genererats vid en egendom i regionen Tanga (Tanzania) för att generera biogas, som också kunna producera el och värme i kraftvärmeverk. Med tanke på den betydande mängd avfall som producerar varje dag, är målet för projektet att hitta en lösning som egendomens ägare, miljön och lokala samhällen kan dra nytta av. Det potentiella utbytet av biogas med dagens produktionsvolym är ca 1,200,00 m³ per år. Detta motsvarar ca 2,340 MWh el samt 4,160 MWh värme per år.

Olika potentiella tillämpningar för biogasen och biprodukterna har analyserats och jämförts för gällande lokala förutsättningar. Resultaten av studien tyder på att lösningen för att maximera sociala, ekonomiska och miljömässiga fördelar är att leverera en del av den biogas som framställs till de omgivande byarna för dess användning som bränsle för matlagning. Resten av elen ska tillföras elnätet. Plantagen köper sedan den el som krävs för den egna produktionen. Resultaten uppgår till ett positivt nettonuvärde (NPV) på omkring 1 580 000 USD och en återbetalingsperiod som är kortare än 9 år. Samtidigt skulle hushåll och miljön få fördelar av den biogasen genom att undvika de alvarliga problemen som hänger samman med traditionella biobränslen.

Nyckelord:

Hållbar utveckling; Tanzania; landsbygdens elektrifiering; sisal; kraftvärme; anaerobisk rötning; biogas
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List of Acronyms

CDM Clean Development Mechanism
CER Certified Emission Reduction
CHP Combined Heat and Power
DCF Discounted Cash Flow
DM Dry Matter
DNO Distribution Network Operator
DSO Distribution System Operator
EWURA Energy and Water Utilities Regulatory Authority
GDP Gross Domestic Product
LCOE Levelized Cost of Energy
NPV Net Present Value
O&M Operation and Maintenance
REA Rural Energy Agency
SDR Sisal Decortication Residue
SPP Small Power Producer
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<tbody>
<tr>
<td>TSB</td>
<td>Tanzania Sisal Board</td>
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<tr>
<td>TZS</td>
<td>Tanzanian Shilling</td>
</tr>
<tr>
<td>USD</td>
<td>United States Dollar</td>
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<td>VS</td>
<td>Volatile Solids</td>
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1. Introduction

The lack of access to safe and reliable sources of energy is one of the most important obstacles hindering the development of rural societies. As Modi et al. stated, “energy is central to sustainable development and poverty reduction efforts”[1]. Since sustainable development has been the focus of a significant number of policies and studies, especial attention should be paid to providing access to energy services in rural populations. There are several solutions for supplying electricity to these areas. One of the most common ones has been grid extension, although this alternative might not be feasible for populations with challenging geographic locations. Therefore, the choice of one of the solutions over the others is dependent on the particular characteristics of the area under study.

1.1. Background and problem statement

Around two billion people worldwide face an electricity deficit. Nearly half of these people are located in Sub-Saharan Africa [2]. The situation in the region is getting worse on a relative scale, as the development of installed production capacity of many countries does not keep up with the increasing demand for electricity. This is the case for Tanzania, which is one of the countries with the lowest rural electrification rates; less than 5% of the people in rural populations have access to electricity [3]. Furthermore, the main energy source in Tanzania nowadays is still traditional – unsustainable- biomass fuels, accounting for over 90% of the total consumption. Biomass is used for both cooking and, where needed space heating [4]. This has led to different issues, such as deforestation and/or health problems for the households. At the same time, the expected increase in the energy demand in the upcoming years as a result of an increase in the population and commercial activity will exacerbate the deficit in electricity generation, as the demand already exceeds the installed capacity of the country.

Because of the limited installed capacity, numerous blackouts and brownouts affect industries, as well as the households and threaten economic growth. Traditionally, electricity has been made available to rural areas by expanding the grid; however, this becomes more and more complex for remote areas with lower population density, especially given the limited installed capacity, and is therefore not economically feasible in most cases. The traditional way of energy supply and scarcity of electricity services is the source of social, economic and environmental issues, and true sustainability will not be achieved without guaranteeing access to clean and affordable energy services.

Further, new environmental regulations in Tanzania requires the addition of wastewater cleaning for the sisal industry, and has effectively banned production without cleaning.

Therefore, new solutions are needed to ensure access to energy services for the rural populations of Tanzania without damaging the environment and that are economically feasible by making the best possible use of the country’s own abundant resources. One of these potential solutions is the use of biogas technologies based on agricultural waste. The agricultural sector still makes the largest contribution to the Tanzanian economy[5], while producing large amounts of residues that are mostly burnt or left in the field due to lack of options for its reutilization.

Biogas technologies could make use of this waste and benefit the population of Sub-Saharan Africa. Because of its tropical climate and agriculture-based economy, Sub-Saharan Africa is an optimal area for the development of biogas technologies, which are often recognized as one of the most energy-efficient and environmentally adapted worldwide [6].
The anaerobic digestion of the substrate (in this case SDR with adjusted water content) in a biogas plant gives two useful products: biogas and digestate. Further, the AD process reduces BOD and COD levels of the raw substrate. The generated biogas can be used for multiple applications, such as cooking, lighting, heating or power generation. At the same time, the digestate is a highly valued fertilizer [7]. As biogas technologies can work with different substrates, such as animal manure, agricultural crops or food residue, the problem of food security and land use competition is avoided.

Even though the production of biogas from agricultural waste can bring benefits to multiple areas in Sub-Saharan Africa, the optimal way to utilize the different products is highly dependent on the local conditions. A deeper understanding of the surroundings of the project is necessary to have a better insight into the potential impact of the solutions.

2. Research objective

The aim of the research is the study of a new solution for reducing environmental impact and providing energy access to villages in rural Tanzania. The proposed solution is the use of the waste generated at Mkumbara Sisal Estate in the region of Tanga to generate biogas and digestate through anaerobic digestion. The biogas could be further processed in a Combined Heat and Power (CHP) unit to produce electricity and heat. Therefore, the technology would potentially generate four useful products: biogas, electricity, heat, and digestate.

The question that follows then is what possible applications can be found for the products, and which one of these applications will benefit the surrounding populations in the best possible way. The objective of the report is to identify among the possible solutions the one that will maximize the economical profitability and environmental and social benefits, by analysing the various scenarios for the application of the biogas plant products. As a result, the best solution, meaning that with the best technical, economic and environmental potential, will be identified.

Three scenarios will be investigated. In the first scenario the biogas would be supplied to the surrounding villages for its use as cooking fuel. In a second scenario, the surplus electricity produced at the CHP unit will be fed into a mini grid to supply electricity directly to the households. Finally, in the last scenario, the surplus electricity will instead be fed directly into the main grid. The combination of different scenarios will also be analysed.

3. Methodology

3.1. Data collection

Two main methodologies were used for collecting the necessary data for the analysis:

1. Field work

During the research, two visits to the estate were conducted. The first one took place in February, and the objective was an overview of the current state. The second one was a 5 week-visit between May and June, to get a better understanding of the potential of the sisal residue and the impact of the different applications on the local environment, households and industry.

The major activities conducted during the fieldwork were semi-structured interviews with households and other stakeholders and observations of the current situation.
• Household interviews: The semi-structured interviews with the surrounding households had the goal of understanding the current situation and estimate the impact of the proposed solutions in the surrounding population centres and the potential market for the sale of the biogas, electricity and digestate. The template used for the household interviews can be found in the annex.

• Interviews with other stakeholders: Relevant stakeholders were interviewed with different purposes. The Rural Energy Agency (REA) was interviewed in order to get a deeper understanding of the regulation and policies surrounding the project. The Tanzania Electric Supply Company Ltd (TANESCO), which is the national utility and the agency in charge of the feed-in-tariffs in the country, was questioned about the potential sale of electricity to the national grid, including, among other parameters, connection costs and power requirements. Finally, interviews were also conducted at Hale, a sisal estate where a similar project was implemented, in order to inquire about their experience and lessons learned.

• Direct observations: Observations at the estate were useful in order to get familiar with the processing of the sisal and understand how the use of the residues for energy purpose would affect the estate and the surrounding communities. Observations and measurements also led to a more precise estimation of the amount of residue produced and the energy consumption at the estate.

2. Literature review

Literature review was performed at different stages of the research process. At the beginning, a literature review was performed on the background of the biogas technology. Previous studies with similar objectives were also reviewed at this stage.

When data could not be obtained through fieldwork, or when it was not sufficient, sources were used as assumptions for the calculations. Finally, a review on the applicable policies and regulations was performed in order to get a better understanding of the legal framework.

3.2. Data processing

The parameter calculation and evaluation of the potential solutions were carried out in three different stages. The first one included mainly the collection of the necessary data, through fieldwork and literature review, and the design of different technical parameters relevant to the project, such as load curves or size and cost of the components of the biogas plant. Once the process of collecting information was completed the different indicators chosen were quantified in order to assess the environmental, social and economic sustainability of each scenario. Sensitivity analyses were also performed to understand how changes in some relevant parameters could affect the final results. Finally, the results obtained were assessed to provide a final conclusion on the appropriateness of the solutions and future recommendations.
4. Structure of the Report

The report is structured as follows:

In the first section (chapters 1, 2 and 3) the problem and objective of the study are introduced. The relevance and general outline of the project is described.

The second section (chapters 5 and 6) describes some of the terms used in the report and the background of the energy sector in Tanzania, the sisal processing and industry in the country, as well as the basics of the biogas technology. Finally, the local conditions and activity at the selected sisal estate are also described.

The seventh chapter presents the different potential applications of the products of the biogas plant, and how each of them can contribute to the estate and the local populations. The current local consumption and potential for each solution is quantified, and the results from the analysis are presented.

In chapter 8 the social and environmental impact of the project are estimated.

Based on the information presented in previous chapters, chapter 9 gives a comparison of the different scenarios studied.
Finally, chapters 10 and 11 reflect the conclusions and recommendations derived from the project, as well as future work and recommendations.

5. Theoretical Framework

The most quoted definition of sustainable development is the one provided by the Bruntland Report: “ [...] development that meets the needs of the present without compromising the ability of future generations to meet their own needs”[8]. In 2005 the World Summit on Social Development identified the three main pillars of sustainable development: economy, environment and society[9]. In line with this definition, the United Nations and its 193 Member States set 17 global goals, known as “Sustainable Development Goals” (SDG) [10] along with 169 targets which lead the way towards their ambitious vision for a sustainable future. Some of the goals are especially relevant for this project, such as goal number 7 “Affordable and clean energy” and goal number 13 “Climate action”.

The definition of rural areas depends on the particular features of the country; however, in developing countries these are often characterized by sparsely population, geographic isolation and difficulties in accessibility. Rural areas are also affected by high illiteracy rate, gender inequality and lack of access to health care, appropriate infrastructure (roads, markets...) and clean water supply [11]. In these rural areas the electrification rates and load factors are usually low, which increases the cost of delivering energy. The cost of generating energy in rural areas is highly dependent on external factors, such as institutional support, political stability or structure of the energy markets. Thus, in order to decide the most appropriate solution for providing energy access in these areas, whether decentralized systems or grid connections, it is necessary to analyse the particular characteristics of the country under study. Mainali and Silveira used the Levelized Cost of Energy (LCOE) as an analysis tool to compare the appropriateness of different technologies for energy access in Afghanistan and Nepal [12].

6. Background

6.1. Area of Research

Tanga region is located in the North-East corner of the country, sharing borders with Kenya to the North, Morogoro and Coast regions to the South, Kilimanjaro and Arusha regions to the West and the Indian Ocean to the East. It comprises seven districts: Lushoto, Korogwe, Muheza, Tanga, Pangani, Handeni and Kilindi. The region has an area of 26,808 km², of which 17,000 km² are arable land [13].

The Mkumbara Sisal Estate is located in the district of Korogwe, in the ward of Mazinde.

6.1.1) Population

According to the 2002 Population and Housing Census, Tanga region is the 10th most populated region out of the total 21 in Tanzania, with 1,642,015 inhabitants. The literacy rate of the region is 70%; however, this percentage varies significantly between male (82%) and female (48%) literacy [13]. The population of the ward of Mazinde is 22,832 [14].
6.1.2) Climate

The climate in Tanga region is warm and wet along most of its extension. The coolest month is June, with minimum temperature of 20ºC; the hottest month is December, with maximum temperature of 32ºC. There are two rainy seasons: a short one from October to November and a long one from April to May. The amount of rainfall is around 750mm per year in most areas, although along the coast it increases to about 1,100 to 1,400 mm [13].

6.1.3) Agriculture

Agriculture plays an important role in the Tanzanian economy, generating around 69% of the total employment and 31% of the country’s GDP [15]. Most of the agricultural products are food crops. Export and cash crops (mainly coffee, tobacco, tea and sisal) accounted for 8% of the total. Most of the households produce only crops (67.3%). Most of the farmers are smallholders, with an average land area utilized per household is 1.7 ha. The use of fertilizers is low [13].

6.1.4) Deforestation

Around 40% of the area of Tanzania is covered by forests, out of which most of them are woodlands [16]. Tanzanian forests are vital for the rural population of the region and contribute significantly to the country’s GDP. The forestland provides around 90% of the energy supply through firewood and charcoal, 75% of the construction materials, 20.1% of the GDP and between 10 and 15% of the export products [17].

This forested land often falls under village and general land, and therefore the management regime remains unclear. Despite having been recognized as areas of global biodiversity importance, the rates of deforestation in the country have increased to alarming levels. Between the period 1990-2010 the country lost on average 19.4% of the forest cover. By 2014, it was estimated that 38% of the country’s forest area had been lost [18]. Since forests play a vital role in carbon sequestration, the loss of forest cover has resulted in increasing CO₂ emissions in the region. There is a risk that the trend will continue or even worsen given the expected increase in the population and industrial activity.

6.1.5) Energy Sector

Tanzania is a country with diverse energy resources, such as biomass, solar or hydro. However, excluding hydro, only 4.9% of the total renewable capacity has been installed [19], due to limitations such as policy inefficiency or economic constraints.

The energy system is heavily reliant on biomass-based fuels, mainly firewood and charcoal, which account for over 90% of the primary energy supply. Electricity represents barely 1.2% of the total consumption, while coal, solar and wind account for less than 1% of energy used [20]. Electricity generation is based mainly on hydro and natural gas, which together account for around 80% of the total installed capacity, around 1,358 MW [21].

Due to the continuing increase in the electricity demand it is expected that by 2035 the demand will be met mainly by coal (41%), followed by large hydro (35%) and oil and gas (21%). As a result of its dependence on hydropower, the country is also highly sensitive to the changes in rainfall patterns caused by climate change. This often leads to an increase in the share of fossil fuels in the energy mix, which are mainly imported.
The electrification rate is low: around 15.3%, although in rural areas the percentage is significantly lower; 3.6%. Therefore the annual consumption of electricity per capita is low (89 kWh) [5]. The access to electricity is provided mainly by stand-alone PV and mini hydro systems and private diesel generators. The annual energy consumption per capita is 0.47 toe, one of the lowest in the world and even below the average consumption in Sub-Saharan developing countries [5]. The Government-owned utility TANESCO is the main electricity supplier in the country, owning the transmission and distribution.

The quality of energy supply in Tanzania is low, due to reduced reserve capacity, high losses and frequent power outages as a result of droughts (in 2012 there were 6 system blackouts with a total duration of 20.3 hours)[22]. Since no real generation extension plans are being implemented, the generation deficit in the country is likely to remain for several years.

The energy system in Tanga, follows the pattern of the nation. The most prevalent source of energy is also firewood, used by 96.4% of the population followed by charcoal and other minor sources. Electricity accounts for only 0.14% of the total supply:

![Sources of energy for cooking in Tanga region](image)

Some of the most important challenges faced by the Tanzanian energy sector nowadays are the increasing demand, low access to modern energy services that limits agriculture production and income generation, high transmission costs and losses and the extended use of unsustainable biomass. Overall, the system runs in a suboptimal way and the generation expansion plans of the country are predominantly dismissing renewables, increasing the installed capacity of gas and coal instead.

The electrification rates of the country have only improved slightly since 1991 and have even decreased in some areas. To improve this data, the Renewable Energy Agency (REA) was created in 2005, which promotes and provides financial support to renewable energy projects, while TANESCO is responsible for grid extension. Several studies have suggested that villages can manage their own electricity supply system if given technical and financial support [23].

### 6.2. Sisal industry in Tanzania

The sisal sub-sector is one of the most important ones in Tanzania, as well as one of the longest surviving agricultural industries in the country. The plant *Agave Sisalana*, commonly known as
sisal, was introduced in 1893 from Mexico, via Hamburg to Tanga. By 1904 around 2,000 hectares of sisal were planted in Tanga and Lindi, and up until 1961 Tanzania was the world's leading sisal producer, producing around 240,000 mt per year [24]. From that year, production experienced a steady decline. In 2013 Tanzania produced around 34,900 tons of sisal, which made the country the second largest producer after Brazil [15]; however, the Tanzanian Sisal Board (TSB) plans to triple exports and increase the sisal production to about 200,000 tons by 2020 [25]. There are several large sisal companies in the country. Katani Ltd and D. D. Ruhinda & Co. Ltd (owner of Mkumbara Sisal Estate) are privately owned and possess all processing facilities, warehouses and camps in the estates [26].

Because of its physical properties, such as strength or ability to stretch, it was traditionally used for agricultural twine. Other uses include rope, paper, mattresses, carpets or clothes. Sisal has also applications in the construction and automotive industry. Sisal products are biodegradable and natural.

The sisal leaves are typically around 120 cm long and contain about 1,100 fibres. In a decorticator these leaves are processed into sisal fibre. In most estates, the decorticators used, which are mostly stationary, are old and inefficient, and as a result their consumption of power and water is high, with a water requirement of around 36,000-45,000 liters per hour to wash the fibre and remove the waste [24]. After this, the fibre is sun-dried in drying lines, and is then brushed, graded and pressed into bales. In a second phase, the fibre is woven into the different products, such as rope, twines, or yarn.

Even though the fibre is the main product, it constitutes only 2.5% of the plant. The other 97.5% is regarded as waste. The waste consists mainly of pulp and wastewater. Around 19 tons of wet waste are produced along with every ton of dry fibre [27]; this waste is often dumped close to the factory; then, the water percolates through the soil and the pulp is left to rot. This causes two types of pollution: the most direct one is caused by the wastewater, which is acidic and pollutes the rivers that supply rural populations. These emissions have recently been regulated and the regulations are increasingly enforced under the new administration. The second polluting effect is caused by the emission of methane during the rotting of the pulp. This highlights the importance of identifying productive uses for the waste, in order to reduce the pollution and create and additional source of income.

6.3. Mkumbara Sisal Estate

6.3.1) Local conditions

Mkumbara Sisal Estate is located in Korogwe district, in the region of Tanga, in Tanzania.
Agriculture is the main activity of the local communities in the area, mostly focused on subsistence farming. The crops include banana, maize, papaya, pepper or tomato, among others. Some communities use the wastewater from the sisal estate for irrigation purposes.

According to Nerini et al., the households have lower energy consumption levels. Those connected to the grid use the electricity mainly for lighting (nearly all of them), radio and phone charging (around 80%), for television (15%) and ironing (5%), and the only cooking fuels used are charcoal and firewood [28].

6.3.2) Description of the estate
The estate is owned by DD Ruhinda & CO Ltd. As one of the major sisal producers in the northwest of Tanga region [28], the estate is an important source of employment in the area. The estate has currently around 1,700 hectares under cultivation. It employs 350 workers (45% female and 55% male), out of which 116 work on harvesting the sisal. The main source of expenses at the estate is the human work. The annual expenditure on energy, including electricity and diesel, is around 74,000 USD.

The sisal fibre is produced all year round, although during the dry season the fibre content is lower. No fertilizer is used to grow the sisal.

6.3.3) Sisal processing at the estate

The process of obtaining fibre from the sisal leaves includes the following steps:
(1) Planting
(2) Harvesting
(3) Transportation
(4) Decortication

(5) Fibre
(6) Drying
(7) Brushing
(8) Baling

(9) SDR

Water
Power

Export
Sisal products
Figure 6. Overview of the different steps for processing the sisal
6.4. Waste characterization

The residue produced during the decortication of the sisal leaves at Mkumbara was analyzed by Muthangya [29]. The following composition was found for the residue, both fresh and dried:

<table>
<thead>
<tr>
<th>Determination</th>
<th>Fresh SLDR</th>
<th>Sun dried SLDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total solids (TS)%</td>
<td>14.01 ± 0.1</td>
<td>16.1 ± 0.2</td>
</tr>
<tr>
<td>Volatile solids (VS) (%of TS)</td>
<td>85.5 ± 0.6</td>
<td>84.9 ± 0.2</td>
</tr>
<tr>
<td>Organic carbon</td>
<td>48.3 ± 0.4</td>
<td>45.9 ± 1.3</td>
</tr>
<tr>
<td>Neutral detergent fibres (NDF)</td>
<td>45.5 ± 0.6</td>
<td>43.5 ± 0.2</td>
</tr>
<tr>
<td>Acid detergent fibres (ADF)</td>
<td>43.0 ± 0.2</td>
<td>41.5 ± 0.5</td>
</tr>
<tr>
<td>Lignin</td>
<td>9.2 ± 2.1</td>
<td>5.5 ± 2.1</td>
</tr>
<tr>
<td>Cellulose</td>
<td>68.6 ± 1.6</td>
<td>72.3 ± 2.2</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>3.5 ± 0.3</td>
<td>7.96 ± 0.31</td>
</tr>
<tr>
<td>Chemical oxygen demand (g/l)</td>
<td>19.6 ± 0.2</td>
<td>Not determined</td>
</tr>
<tr>
<td>pH</td>
<td>5.8 ± 0.2</td>
<td>Not determined</td>
</tr>
</tbody>
</table>

Table 1. Composition of the SLDR at Mkumbara

The Chemical Oxygen Demand (COD) of the waste is greater than the permissible limit for municipal and industrial effluents allowed by the regulation, 60 mg/l [30]. Anaerobic digestion can reduce the presence of COD in the waste by up to 70-90% [31], thus avoiding potential penalties by the government.

Furthermore, the studied qualified the residue produced at the estate as being suitable for anaerobic digestion in the production of biogas.

6.5. Biogas technology

Biogas is produced by the anaerobic digestion of organic material in digesters and biogas plants. It is a gaseous biofuel consisting mainly of methane (CH₄) (55-65%) and carbon dioxide (CO₂) (35-45%), with a calorific value between 19.7 and 23.3 MJ/m³, depending on the proportion of CH₄ [32]. Purified biogas has similar characteristics and applications to natural gas.

Several types of products can be used as input, including animal manure, agricultural residues or municipal solid waste. Another advantage of biogas technologies is that they are flexible in design and scale. Therefore, biogas systems can be designed for both household and industrial applications. The two main products of the anaerobic digestion are the biogas itself and the digestate. In turn, the biogas has multiple applications: it can be used for cooking, lighting, heating or power generation. The digestate can be utilized as a fertilizer [7].

6.6. Biogas in Sub-Saharan Africa and Tanzania

Because of its tropical climate, lower land and labour costs and agriculture-based economy, Sub-Saharan Africa is an optimal area for the development of biogas technologies [33]. At the same time,
bioenergy production and trade in developing countries can contribute to their development by promoting rural employment and raising and diversifying farm income.

The use of biogas technologies in Tanzania began in the 1970s, when the Small Industries Development Organization (SIDO) started installing floating-drum biogas digesters in the country. However, the diffusion of biogas technologies began with the implementation of the Tanzania Domestic Biogas Programme in 2009 [34]. Since then, the presence of the technology in the country has been increasing, supported by the Government through different programs and funding mechanisms. The main barrier for its further expansion is still the high installation and maintenance costs and the lack of technical expertise.

Traditionally, the biogas sector in Tanzania has put emphasis on the use of animal manure as a feedstock. However, there is a large potential for the use of agro-industrial residues, as these materials have a high organic matter content and the traditional methods for disposing them is an important source of pollution. Kivaisi and Rubindamayugi estimated the energy potential of agro-industrial residues in Tanzania to be 1,135 Million kWh, out of which 240 Million kWh would come from sisal [35].

### 6.7. Biogas applications

#### 6.7.1) Electricity generation

The properties of biogas make it a suitable fuel for an internal combustion engine. If the engine is coupled with a generator (generator-set or genset), electricity can be generated. A conversion rate of 1.7 kWh/m³ can be achieved [36], although some technologies can reach efficiencies of up to 33% [37]. Natural gas or propane engines can be adapted to burn treated biogas [38]. A second option for power generation is to use a gas turbine. However, this technology is more suitable for large-scale applications, where the electricity demand is at least equal to the output of the turbine and where continuous operation is required [39]. Therefore, for small-scale applications (up to 5 MW) it is recommended to use an engine instead of a turbine, since the cost is lower and the efficiency is higher.

One possible application of the electricity is its use in the production of the fibre, which is an energy intensive process. At the same time, due to the unreliability of the electricity sector in Tanzania, the electricity generated using biogas could provide a more stable power supply for surrounding rural households.

#### 6.7.2) Heat generation

Using biogas in boilers to generate heat is one of the most common and simple applications, with high conversion efficiencies (around 75-85%) [32]. Biogas can be burnt in the same boilers used for natural gas, with only a few adjustments. The heat generated from the waste can be used to maintain the conditions in the anaerobic digester.

#### 6.7.3) Cogeneration of heat and electricity

By using a combined heat and power plant (CHP), heat and electricity can be generated simultaneously from the biogas. In CHP plants, electricity is generated by burning the biogas, and then the heat from the exhaust stream or the engine jacket is captured by a heat recovery unit. The heat can be converted into useful thermal energy in the form of steam or hot water.
Terrapon-Pfaff et al. have quantified the energy potential of sisal residues. The following table shows the amount of energy and heat that could be obtained from sisal pulp, sisal ball and wastewater per ton of fibre produced:

<table>
<thead>
<tr>
<th>Residue type</th>
<th>Energy type</th>
<th>Energy potential (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sisal pulp</td>
<td>Electricity</td>
<td>1,200-3,000</td>
</tr>
<tr>
<td></td>
<td>Heat</td>
<td>1,500-3,500</td>
</tr>
<tr>
<td>Sisal ball</td>
<td>Electricity</td>
<td>1,600</td>
</tr>
<tr>
<td></td>
<td>Heat</td>
<td>2,000</td>
</tr>
<tr>
<td>Wastewater (100 m³)</td>
<td>Electricity</td>
<td>1,200-1,500</td>
</tr>
</tbody>
</table>

Table 2. Energy potential of sisal waste per ton of fibre [4]

6.7.4) Fuel for transport

Using the biogas as fuel for vehicles requires additional cleaning and upgrading to biomethane, which has a similar quality to natural gas [40]. There are a few tractors on the market that can run on biomethane; however, the sector is still under development and further research is needed. Therefore, use of the biogas for transport applications is unlikely, as it would require gas upgrading equipment and a fuelling station, as well as the purchase of new vehicles.

6.7.5) Biogas as a cooking fuel

The use of traditional cooking fuels, mainly charcoal and firewood, is dominant in Tanzania. In the region of Tanga almost 97% of the population relies on firewood as an energy source [13]. This has led to several issues, such as indoor air pollution and deforestation. Furthermore, the responsibility of acquiring the fuel, which is a time-consuming activity, often relies on women, which reduces the time available for social activities or education. Biogas can act as a replacement for these fuels, as it has a higher efficiency and can help avoid the aforementioned issues.

6.7.6) Digestate as a fertilizer

Digestate is another product of the anaerobic digestion, which consists of the feedstock materials after the biogas has been extracted. By using this digestate as a fertilizer, the nutrients and organic content can be recycled in a sustainable way. For this application it is particularly important to have adequate levels of composition and quality of the digestate, which are heavily dependent on the composition and quality of the feedstock. The fertilizer can be used at the site or sold to third parties. When used at the estate, the digestate can improve soil fertility and increase the yields [4]. The organic matter and nutrient content (N, P, K and Mg) of the digestate after the anaerobic digestion makes it a suitable fertilizer for agricultural soil, improving its quality and water-holding capacity and stimulating microbial activity, which results in higher crop yields.

Muthangya et al. analysed the nutrient content of a sample of SDR from Mkumbara estate and found the following composition:

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Content [mg/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorous</td>
<td>0.161</td>
</tr>
</tbody>
</table>
Due to its low dry matter content, the storage, transport and application of the digestate can be expensive. There are several methods for separating the solid and liquid fraction of the digestate. The solid fraction can be applied directly as a fertilizer or stored, whereas the liquid fraction, the leachate, which contains most of the nitrogen and potassium can be either applied as a fertilizer or re-fed to the digester [41].

It is recommended that the digestate is used only during the growing season, in order to avoid water and air pollution [41]. Therefore, storage solutions for the digestate should be considered, whether it is done at the biogas plant or at a nearby location. However, open-air storage can lead to acidification and eutrophication due to ammonia leakage [42]. Covered tanks and methane capturing are therefore recommended.

Neal et al. studied the use of the effluent from an anaerobic digestion plant using kitchen waste to grow tomatoes hydroponically [43]. Although the study showed potential for this application, high amounts of ammonium in the digestate can represent a limitation.

### 6.8. Legal and regulatory framework

The National Energy Policy of Tanzania (2015) [44] recognizes the key role played by biomass in meeting the energy needs of the households and states that efforts have been made by different development partners to promote projects that generate electricity from biogas in the country. However, it is also stated that the support for generating electricity from agricultural waste has been inconsistent, and that the technology should be further promoted. Regarding the production and utilization of gaseous biomass the policy states that the government shall “promote proper management of bio-waste feedstocks for power generation and waste management; ensuring a stable environment for production and utilization of gaseous biomass; promote modern use of gaseous biomass for the generation of electricity and provide incentives for private investment in bio-electricity generation” [44].

However, the policy also recognizes that an adequate legal and regulatory framework is still needed in order to successfully implement the objectives and strategies that were set. Overall, the current policy is vague when it comes to setting goals for the diffusion of renewable energy technologies or strategic implementation plans (short, medium and long term).

The National Environmental Policy (1997) reflects the importance of the environment in the Tanzanian society, as a significant part of the population relies on agricultural activities for their livelihood. The policy recommends waste management and an efficient use of resources [45]. One of the stated goals of The National Employment Policy (1997) is “to identify potential areas for employment and to lay down strategies of how to utilize such areas in promoting employment in the country” [46]. As the biofuel sector represents an opportunity for creating new jobs, it is in line with the objectives of the policy. Finally, as large-scale cultivation of sisal could potentially threaten the biodiversity of the region, the Environmental Management Act (EMA) (2004) requires conducting environmental impact assessments (EIA). The EMA also mentions the use of taxation schemes for
environmental protection, such as lower taxes on environmentally friendly technologies or products, which could apply to the production of biofuels.

7. Results and Discussion

7.1. Resource assessment

The theoretical energy potential of sisal waste for this project was estimated based on the fibre production at the estate during the year 2016. Measures during the field work suggest that the fibre content of the sisal leaves is around 2.5%. With this data, the amount of residue available was estimated. The biomass would then be fed into a gasifier to generate the biogas. Table 4 sums up other assumptions used to calculate the biogas potential from the fibre production:

![Fibre production (2016)](image)

Figure 7. Reported fibre production at Mkumbara Sisal Estate in 2016

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fibre produced in 2016</td>
<td>752.35 tons</td>
<td></td>
</tr>
<tr>
<td><strong>Average SDR production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas yield</td>
<td>196 m³/tonne VS</td>
<td>[36]</td>
</tr>
<tr>
<td>% DM in SDR</td>
<td>14%</td>
<td>[29]</td>
</tr>
<tr>
<td>% VS in DM</td>
<td>85.5%</td>
<td>[29]</td>
</tr>
<tr>
<td>Methane content in biogas</td>
<td>60%</td>
<td>[47]</td>
</tr>
<tr>
<td>Energy content of methane</td>
<td>10 kWh/m³</td>
<td>[47]</td>
</tr>
</tbody>
</table>

Table 4. Production parameters at the estate
Based on the previous assumptions it was estimated that the sisal residue could produce 1,177,576 m$^3$ of biogas per year. This yield would increase with larger harvested volumes. It was noted, however, that the value of the amount of SDR produced has some uncertainty. Factors like the electricity availability, the presence of floods or increased financial support from the government have significantly affected the amount of SDR produced in previous years. At the same time, the owners of the estate have plans to expand the planted area by 100 ha per year for the following years, which would mean an increase in the production. Therefore, a sensitivity analysis was performed to estimate how the amount of biogas produced would change if the amount of SDR varied by 25%:

<table>
<thead>
<tr>
<th>Variation in amount of SDR</th>
<th>Biogas production [m$^3$/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25%</td>
<td>883,182</td>
</tr>
<tr>
<td>0</td>
<td>1,177,576</td>
</tr>
<tr>
<td>+25%</td>
<td>1,471,970</td>
</tr>
</tbody>
</table>

Table 5. Sensitivity analysis of the electricity and heat production based on the SDR production

Therefore, the amount of residue produced at the estate would have considerable impact on the energy production and plant capacity. It is therefore important to have a low degree of uncertainty when estimating this factor.

### 7.2. Electricity and heat production

After calculating the amount of biogas produced, the next step is to estimate the amount of electricity and heat that can potentially be obtained from the biogas. The proposed solution is the use of a gen-set that combusts the biogas, producing electricity and heat. The overall and electrical efficiency of the CHP process is assumed to be 92% and 33%, respectively [48]. With these assumptions, it was estimated that 2,340 MWh of electricity and 4,160 MWh of heat can be produced each year by utilizing the sisal residue. The three previous scenarios of SDR production (±25% variation) were also considered for the sensitivity analysis of the electricity and heat production:

<table>
<thead>
<tr>
<th>Variation in amount of SDR</th>
<th>Electricity production [MWh/yr]</th>
<th>Heat production [MWh/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25%</td>
<td>1,755</td>
<td>3,120</td>
</tr>
<tr>
<td>0</td>
<td>2,340</td>
<td>4,160</td>
</tr>
<tr>
<td>+25%</td>
<td>2,925</td>
<td>5,200</td>
</tr>
</tbody>
</table>

Table 6. Variation in the production of power and heat as a result of variations in the amount of resource available

### 7.3. Energy consumption at the estate

The two energy sources used at the estate are electricity and diesel fuel. The electricity demand comes mainly from the equipment used to process the sisal and to a lesser extent to supply electricity to the village closest to the estate. This village consists of approximately 40 households where some of the estate workers and their families live. Nowadays, the estate owner provides
electricity for them free of charge. The following table shows the power rate of the electrical machinery of the estate and the working hours per year:

<table>
<thead>
<tr>
<th>Machinery</th>
<th>Units</th>
<th>Power rate (kW)</th>
<th>Hours/year</th>
<th>Power consumption (MWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press machine</td>
<td>1</td>
<td>9</td>
<td>1,964.5</td>
<td>17.60</td>
</tr>
<tr>
<td>Brushing machine</td>
<td>3</td>
<td>18</td>
<td>1,964.5</td>
<td>105.52</td>
</tr>
<tr>
<td>Decorticator</td>
<td>1</td>
<td>96</td>
<td>3,026</td>
<td>290.08</td>
</tr>
<tr>
<td>TOTAL (MWh/year)</td>
<td></td>
<td></td>
<td></td>
<td>381.95</td>
</tr>
</tbody>
</table>

Table 7. Power consumption of the machinery using electricity at the estate [49]

The calculations above show that the decortication is the most energy intensive process.

Diesel fuel is used at the estate with two purposes; to power the tractors and caterpillars that prepare the land and transport the sisal leaves, and as fuel for the back-up generator that is used when there are blackouts in the national grid. The caterpillars and tractors use around 46,800 l of diesel per year [28], and the consumption of the generator is 2,500 l per month, or around 322 MWh per year. Therefore, over 64% of the diesel fuel bought at the estate is used only for covering the electricity demand when there the power coming from the national grid is out. By generating electricity from the sisal waste no electricity needs to be purchased from the grid, and diesel will only be needed for the caterpillar and tractors.

7.4. Application of biogas products

7.4.1) Electricity

The overall demand of electricity at the estate is a little below 400 MWh per year, whereas the internal consumption of the biogas plant was estimated as 20% of the production [49]. Therefore, in the base scenario, the amount of electricity produced in the CHP unit would be enough to cover the internal demand and still produce over 1,490 MWh of excess electricity per year, almost 64% of the production.
One potential use for this excess electricity is to feed it into the main grid. Since increasing access to energy services is one of the main goals of the country’s policies and TANESCO has problems meeting the increasing demand, the Tanzanian government offers a feed-in-tariff. For Small Power Producers (SPP) (between 100 kW and 10 MW at 33 kV or below) the regulation, called “Grid interconnection of small power projects in Tanzania” [50], establishes that the DNO (TANESCO) must take all the net electricity output produced by the Seller and sold to the DNO. It also sets the procedure to establish the feed-in-tariffs. If the electricity is sold to the main grid, then the tariff is calculated as the avoided cost of power purchases and power generation by the DNO. This tariff was 190.46 TZS/kWh (around 0.09 USD/kWh) in 2016. For biomass projects up to 500 kW the tariff is higher, 0.169 USD/kWh [51].

Another option is to feed the electricity into a mini grid. If the electricity is sold to TANESCO the tariff is the average between the incremental LCOE from a new mini-grid diesel generator and the incremental cost of new grid-power generation adjusted to remove transmission losses. This tariff in 2016 was 477.16 TZS/kWh (0.21 USD/kWh). In case the electricity is sold directly to customers instead of TANESCO, the tariffs are based on the cost of the project plus a reasonable profit, and they are likely to be higher than the national tariffs, as the priority for the Government is to increase access to electricity. Therefore, selling the excess electricity to nearby rural populations could be a solution to increase economic profitability, especially since the government gives a funding of 500 USD per every new connection to the grid [52]. In order to evaluate the feasibility of this option the main population centres in a 5 km radius from the estate were identified:

![Population centres in a 5 km radius to the estate (Source: Google Earth)](image)

An estimation of the amount of households in each village was done through observation on the map. Overall there are 931 households in the area that could be supplied with electricity. Since the average household size for rural populations in Tanzania is 5 people [14], the estate could potentially supply electricity to 4,465 people.

| Total number of households in 5 km radius | 931 |
| Number of potential consumers | 4,655 |

Table 8. Estimation of the power demand of the villages surrounding the estate
Alternatively, electricity could be sold to TANESCO’s main grid. The closeness of the estate to the 33 kV line would significantly decrease the connection costs.

Figure 10. Location of TANESCO’s 33 kV line

7.4.2) Heat

The heat generated in the cogeneration will be used to heat up the digester. Supplying excess heat to nearby villages was not considered a feasible option for this study.

7.4.3) Biogas for cooking

Previous studies in Uganda have found that on average, 0.227 m$^3$ of gas per person are required daily for cooking [53]. Using the average rural household size in Tanzania, the daily household demand of gas would be 1,135 m$^3$. Providing biogas for cooking for the 40 households located nearby the estate would therefore require around 16,571 m$^3$ of gas annually, equivalent to less than 100 MWh. Furthermore, the proximity of some of these households to the estate makes it easier to supply the produced biogas through pipelines.

The economic feasibility of this option however remains unclear, since it would lead to a lower production of electricity and heat, and the price charged to the households for the biogas could not be higher than the amount that they currently pay for firewood and charcoal.

7.5. Questionnaire results

Nine out of the ten identified villages were interviewed, as access to village number 9 was limited and therefore not interesting for the project. In each village, a number of households proportional to the size of the village were questioned about their economic situation, energy consumption patterns
and willingness to change. The following table shows the estimated population and distance to the estate of each one of the villages:

<table>
<thead>
<tr>
<th>Village number</th>
<th>Village name</th>
<th>Distance to the estate [km]</th>
<th>Estimated population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mkumbara</td>
<td>0.34</td>
<td>165</td>
</tr>
<tr>
<td>2</td>
<td>Magila</td>
<td>0.56</td>
<td>1,434</td>
</tr>
<tr>
<td>3</td>
<td>Mifusini</td>
<td>0.71</td>
<td>659</td>
</tr>
<tr>
<td>4</td>
<td>Tembo</td>
<td>1.60</td>
<td>570</td>
</tr>
<tr>
<td>5</td>
<td>Station</td>
<td>1.66</td>
<td>518</td>
</tr>
<tr>
<td>6</td>
<td>Kwenangu</td>
<td>2.74</td>
<td>761</td>
</tr>
<tr>
<td>7</td>
<td>GohaChini</td>
<td>4.23</td>
<td>950</td>
</tr>
<tr>
<td>8</td>
<td>GohaMigonbani</td>
<td>2.13</td>
<td>194</td>
</tr>
<tr>
<td>10</td>
<td>Kimunya</td>
<td>3.82</td>
<td>195</td>
</tr>
</tbody>
</table>

Table 9. Name, distance and population of the villages

Overall, the total sample size was 45 households. In each interview, three employees from the estate were present, acting as translator and intermediaries.

Regarding population statistics, from the interviews it was found that the average household size was 5.84 (3.05 female and 2.80 male). Even though TANESCO has provided grid extension in 7 out of the 9 villages, the electrification rate is low, around 24%. The average monthly income of the households is 217,301 TZS (around 100 USD), with the main sources of income being agriculture (58%) and business (23%). Other minor sources of income are fishing (6%), workers at the sisal estate (2%) and daily workers (12%). All of the interviewed households identified food as being the main expenditure; in some cases, this expenditure was even larger than the household income.

![Figure 11. Monthly expenditure of the households by source](image)

Food was also identified as the number one priority for most of the households, followed by education, clothes and health services.
As for the choice of cooking fuel, firewood and charcoal are the most popular options. Firewood is used in 84% of the households, and it is mainly collected. 80% of the households use charcoal: on average 49 kg of charcoal are used per month. Charcoal is bought in tins, at a price of 3,000 TZS (around 1.34 USD) per tin (1 tin contains between 8 and 10 kg of charcoal). Most households own both a firewood and a charcoal stove, and use one fuel or the other depending mainly on the economy of the households. Other cooking fuels used are kerosene (used by 7% of the households) and LPG (used by only 2%).

![Firewood and charcoal stoves](image)

Figure 12. Example of firewood (left) and charcoal (right) stoves used in the villages

When questioned about their level of satisfaction with the current cooking fuel, all the households indicated that they are not satisfied and are willing to change. The main reason for this is the difficulty in access to the cooking fuel, because of economic barriers (in the case of charcoal) or collection time (for firewood). After a brief explanation of the origin of the biogas and the biogas stoves available in the market all the households seemed interested in using this technology and found the price of the stoves affordable.

Regarding the electricity consumption patterns, most households still lack access to electricity. A small percentage relies on solar power. As for the electricity demand, it comprises mainly lighting, which is done through solar and kerosene lamps when electricity is not available, radio and TV and phone charging. The results from the interview show that 89% of the households have at least one mobile phone, with an average of 2 phones per household. The following most common appliances are lamps (51% of households), radio (44%), TV (22%) and fridge (9%). Only 2% of the households have a computer or a fan.
Overall, the estimated electricity consumption per capita is 59 kWh/year, lower than the national value, 89 kWh/year [5].

Finally, diseases associated with cooking fuel, such as respiratory diseases or eye infection were present in 38% of the interviewed households and those associated with water, mainly typhoid and diarrhoea, in 33% of the households.

7.6. **Load assessment**

An estimation of the demand that is as accurate as possible is crucial for the whole system modelling and result analysis. In this case there are two main loads to consider: the villages and the sisal estate itself. From the questionnaire results it was understood that the demand of the villages is low, whereas in the case of the estate it is considerably higher due mainly to the decortication process, which is highly energy intensive.

7.6.1) **Village load**

Based on the result of the interview, the load of the villages has been estimated for three different scenarios. In the first scenario only basic services (lighting) is provided. As a result, less power is required in comparison with the current situation. In the second scenario, “evening services”, the demand is higher during the evening hours, due to equipment such as radio, television or phone charging. The last scenario also includes productive uses of power during off-peak hours. The purpose is to increase the agriculture production of the households, which could potentially increase their income. As this scenario represents a considerable increase in the energy demand, it will only be applied to the village adjacent to the estate (village number 1). The demand of the other population centres will remain the same as in the second scenario.

<table>
<thead>
<tr>
<th>Scenario 1: Basic services</th>
<th>Load</th>
<th>No. of units</th>
<th>Power [W]</th>
<th>Hrs/day</th>
<th>Wh/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-energy lamps</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1,000</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2: Basic + “evening” services</th>
<th>Load</th>
<th>No. of units</th>
<th>Power [W]</th>
<th>Hrs/day</th>
<th>Wh/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>1</td>
<td>4.8</td>
<td>6</td>
<td></td>
<td>28.8</td>
</tr>
</tbody>
</table>
Table 10: Energy consumption of the villages for the three proposed scenarios

Based on the hours of usage of each of the appliances, the load curve for each of the scenarios would look as follows:

Figure 14. Load curve of the households in “Basic services” scenario
7.6.2) Estate load

In previous sections the energy consumption of the estate itself was estimated. The load curve of the sisal estate can also be established knowing the consumption of the different machines and the hours of usage. The decorticator is used during the working hours at the estate, from 6.00 to 17.00, with two breaks in the middle (from 9.00 to 10.00 and from 13.00 to 14.00). Therefore, the load is heavily concentrated during those hours. The other machines used at the estate, for brushing and pressing, have similar operating hours:

7.7. Biogas scenario

The results from the interviews indicate that each household uses on average 49 kg of charcoal per month. The amount of firewood used cannot be easily quantified since it is mostly collected, not
bought, when charcoal is not available or affordable. Therefore, it will be assumed that charcoal is the only cooking fuel used.

The efficiency of the charcoal stoves is low: for traditional stoves in Tanzania a value of 15% efficiency can be assumed [55]. As for the gas stoves, the efficiency is considerably higher. For this study, this efficiency is estimated as 45% [56]. Using the calorific value of both fuels, it was estimated that each household would require around 23 m$^3$ of biogas for cooking per month. Assuming that all the generated biogas is used for cooking purposes, over 4,300 households could be supplied with cooking fuel, assuming also that the energy losses are negligible. This amount is greater than the estimated number of households in a 5 km radius. Therefore, part of the biogas can still be converted into electricity to meet the power requirements of the sisal estate and the biogas plant itself. Even in this case, there is still potential for supplying biogas to the 9 villages.

Based on the estimation of the number of households, biogas could be supplied to villages 1, 2, 3, 4 and 5, all of them at a distance of less than 2 km from the estate. Additionally, villages number 6, 10 and 7 could also be included, although the distance in this case is greater. Villages number 8 and 9 have been ruled out, the first one for being a Maasai village and the second one for the difficulty in access.

7.7.1) Parameter calculation

The estimated biogas consumption of each household was 22.69 m$^3$/month. Assuming that there are three use periods for the cooking fuel (from 6.00 to 8.00, 12.00 to 14.00 and from 19.00 to 21.00), and that each period uses 0.25 m$^3$ of biogas, the gasflow required for the 911 households is approximately 113 m$^3$/h.

The pressure drop can be estimated using the general formula:

$$\Delta p = \frac{4 \cdot f \cdot \rho \cdot v^2 \cdot L}{2 \cdot d} = \frac{32 \cdot f \cdot \rho \cdot L \cdot Q^2}{\pi^2 \cdot d^5}$$

Equation 1. General formula for calculation of pressure drop

Where;

$\Delta p;$  pressure drop [Pa]

$f;$  friction factor (0.006)

$\rho;$  density (1.13 kg/m$^3$)

$L;$  length of the pipe [m]

$Q;$  gas flow (0.0314 m$^3$/s)

d;$  diameter (2.54·10⁻² m)
Then the maximum pressure drop (for village 7, at 4.23 km from the estate), the pressure drop is $8.96 \times 10^6$ Pa, or 9 bar, which needs to be compensated, using for example a compressor. However, if biogas is only supplied to the nearest villages at a distance to the estate of less than 2 km, the pressure drop would decrease to 1.26 bar, which would require a compressor of a smaller size. The gas flow in this case would also be lower; 69 m$^3$/h.

### 7.7.2) Cost estimation

There is, on one hand, the cost of constructing the biogas plant itself and, on the other, the cost of building the system for distributing the biogas to the households. The cost of the biogas plant has been calculated based on the plant design and sizing as estimated by Fuqoha. The cost of the plant has been divided into equipment costs, construction costs and external services. The cost breakdown can be found in appendix B.

<table>
<thead>
<tr>
<th>Type of cost</th>
<th>Total cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>804,840</td>
</tr>
<tr>
<td>Construction</td>
<td>30,134</td>
</tr>
<tr>
<td>External services</td>
<td>264,931</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1,099,905</strong></td>
</tr>
</tbody>
</table>

Table 11. Capital cost of the biogas plant[49]

The yearly costs related to the operation and maintenance of the plant, as estimated by Oudshoorn, are 61,100 USD [27]. However, it is difficult to know how precise this estimation is, as the O&M costs of a biomass plant can range between 1 and 6% of the capital cost [57]. Therefore, a sensitivity analysis will be performed for this parameter.

As for the cost of the distribution system for supplying the biogas to the households, it is as follows. The length of the piping system has been calculated assuming that all the households in the 5 km radius would be supplied with cooking fuel:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost [USD/unit]</th>
<th>Unit</th>
<th>Total cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanized steel pipes (1½&quot;)</td>
<td>3.43 USD/m</td>
<td>11,210 m</td>
<td>38,450.30</td>
</tr>
<tr>
<td>Valves</td>
<td>2,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>2,000</td>
<td>1</td>
<td>2,000</td>
</tr>
<tr>
<td>Gas meters</td>
<td>7,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL COST</strong></td>
<td><strong>50,450.3</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12. Capital cost for biogas supply

### 7.7.3) Appropriateness of the solution

The use of biogas as cooking fuel will only be successful if the villagers have an accepting attitude towards the project. A key parameter in that regard is the price charged for the biogas, which needs to be affordable given the average income of the households. From the results of the interview the expenditure in cooking fuel (mainly charcoal) was estimated at around 14,000 TZS (6.25 USD) per
month, close to 5% of the average monthly income. The price of the biogas stoves (40,000 TZS for the single stove and 75,000 TZS for the double) was seen as affordable by the majority of the households. In order to keep the cooking fuel expenditure at a similar level, and based in the monthly expected biogas consumption, around 620 TZS (0.28 USD) can be charged for every m³ of biogas.

Once the costs have been estimated, the economic feasibility of the solution can be studied by comparing the costs and revenues. If the biogas is supplied to some of the surrounding villages for its use as cooking fuel the following revenues can be expected:

<table>
<thead>
<tr>
<th>Source</th>
<th>Revenue [USD/unit]</th>
<th>Unit</th>
<th>Total revenue [USD/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity savings</td>
<td></td>
<td></td>
<td>32,054.84</td>
</tr>
<tr>
<td>Diesel savings</td>
<td>0.83 USD/l</td>
<td>30,000 l/yr</td>
<td>24,900.00</td>
</tr>
<tr>
<td>Biogas sale</td>
<td>75.96 USD/hh</td>
<td>911 hh</td>
<td>69,203.46</td>
</tr>
<tr>
<td><strong>TOTAL REVENUE [USD/yr]</strong></td>
<td></td>
<td></td>
<td><strong>126,187.19</strong></td>
</tr>
</tbody>
</table>

Table 13. Sources of revenue for the biogas supply scenario

The electricity and diesel savings have been calculated based on the estate’s expenditures as demonstrated. Since the price of the diesel fuel has been increasing and decreasing in previous years without a noticeable pattern it has been assumed to be stable. However, instabilities in the Tanzanian energy system have caused the electricity prices to increase at a sharp rate in the past. The average annual increase in the past 10 years, 12% [55], has also been used to estimate the electricity savings in the future. Finally, even though the production of biogas is expected to increase throughout the lifetime of the project, it is unlikely that cooking fuel will be supplied to any more households, as there are no more available customers in the 5 km radius and expanding the distribution system would be too complicated. However, for the calculations, an increase in the price of the biogas of 3% every 5 years has been considered.

Under those assumption, and with a discount rate of 8% [49] and a project lifetime of 15 years, the discounted cash flow has been estimated. For every year during the lifetime of the project the cash flow is defined as the difference between the revenues (electricity and diesel savings and biogas sale) and the costs (O&M cost of the biogas plant) for that year. The discounted cash flow (DCF) takes into account the time value of money and is, therefore, a more accurate analysis.
From the analysis it is clear that the project would not be profitable under the assumptions made, with an NPV at the end of its lifetime of -259,912 USD. The minimum price of biogas that would make the project profitable is 0.40 USD/m³, which would increase the cooking fuel expenditure of the households to 9.3% of the average income, compared with the current percentage of 5.2%. Previous authors have assumed a price of the biogas equal to 10% of the income, considering it an affordable level for the households. However, even though a higher price for the biogas would result in a more profitable project, it could also threaten the acceptability of the biogas technology by the households, risking the outcome of the project.

Furthermore, the LCOE is higher compared to the values found in the literature. The cost of producing biogas merely for cooking purposes was estimated to be 0.58 USD/kWh, whereas, according to previous studies, the LCOE of biogas technologies usually ranges between 0.17 and 0.25 USD/kWh [65]. The reason why the LCOE is higher for this project is that the biogas demand of the surrounding villages is low, and therefore almost half of the biogas production would remain unutilized.

There are also several variables that condition the profitability of the project and are hard to estimate accurately, such as the future increase in electricity prices, the yearly O&M costs of the biogas plant or the discount rate. Sensitivity analyses have been performed for these variables in order to study how they can affect the final result.

- **Future electricity price:** For the base scenario the average increase in electricity prices in TANZANIA in the last 12 years, 12% [58] has been used as an assumption to project the future electricity savings, even though during that time period, the annual increase has reached values higher than 40% (2011-2012). Therefore, the NPV of the project has been calculated varying the original percentage by 25%. The results (Figure 18) show that the minimum average annual increase in the electricity prices that would make the project profitable is 17.02%. Looking at the evolution of electricity prices in past years it seems unlikely that the tariffs will experience such a sharp increase in the future. Therefore, the feasibility of the project cannot rely on this variable.

- **O&M costs:** As stated earlier, the O&M costs of a biomass plant can range between 1 and 6% of the capital cost. For the baseline the variable cost of the project was set at 61,100 USD/yr, close to 6% of the capital investment. The sensitivity analysis reflects the NPV of the project...
for variations of this value from -25% to 25%. As with the previous case, the sensitivity study shows that the project would still remain unfeasible. The maximum annual O&M cost that would make the project profitable is 32,320 USD. Although this breakeven point is around 3% of the capital cost, and therefore is still inside the limits suggested by the literature, it represents a decrease of 47% compared to the original value. Again, it is unlikely that said value can be achieved.

- **Discount rate:** For the base analysis a discount rate of 8% was used. In the sensitivity analysis the effect of the discount rate was assessed by varying its value from 5 to 10%. Even though lower values of the discount rate improve significantly the economic results of the project it would still be unprofitable. The analysis shows that the maximum discount rate that would still result in a profitable project is 4.9%, a value lower than the ones found in the literature.

Figure 18 shows the results from the sensitivity analysis for the three different parameters.
Figure 18. Sensitivity analysis of the biogas scenario for variations on (a) electricity tariff increase (b) O&M costs (c) discount rate.
The results show that this scenario would not be feasible under any of the assumptions. The main reason is the low biogas consumption of the households. As it seems unlikely that the villages would increase significantly their biogas demand or that more households will be connected to the distribution system, the scenario would only be feasible if the villagers are willing to increase the expenditure on cooking fuel compared to the current situation, which might in return threaten the social acceptability of the project.

As there is still a large fraction of the biogas being unutilized, there is potential for using the excess biogas to generate electricity that would then be fed directly into the main grid. More power can be generated if only the villages under a 5 km radius are supplied with cooking fuel, which would reduce also the investment cost, as the length of the piping system and the losses would be lower, although if the system is interconnected to the national grid the interconnection costs should also be included in the capital investment.

Due to the expansion plans of the company it is expected that the production of biogas would increase every year. The annual increase was quantified by Fuqoha [46]. As a result the sales of electricity increase every year, starting from year 5, when the export capacity is large enough to meet the requirements established by the regulation (200 kW). The expected feed-in tariff is the one for biogas projects up to 400 kW, 0.161 USD/kWh [57].

The results and assumptions for this scenario are shown in the table and the figure below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of households supplied with biogas</td>
<td>531</td>
</tr>
<tr>
<td>Benefits – sale of biogas</td>
<td>41,476.50 USD/yr</td>
</tr>
<tr>
<td>Benefits – sale of power (year 5)</td>
<td>299,346.74 USD/yr</td>
</tr>
<tr>
<td>Total capital cost</td>
<td>1,185,522.10 USD</td>
</tr>
<tr>
<td>NPV (year 15)</td>
<td>1,578,986 USD</td>
</tr>
</tbody>
</table>

Table 16. Assumptions and results from the sale of biogas and power
From the results of the discounted cash flow it is clear that supplying biogas to the households that are located inside a 2 km radius and selling the excess power to the grid would significantly improve the economic results of the project. The LCOE in this scenario is 0.25 USD/kWh, closer to the values found in the literature [65]. In this case the project would still be profitable even if the electricity price remains the same in future years or the interest rate becomes as high as 18.8%. The payback period for this scenario is 9 years, whereas supplying all the biogas to the surrounding village will result in payback period of 19 years, higher than the expected lifetime of the project.

7.8. **Mini grid scenario**

Mini-grids based on renewable energy sources can provide reliable and cost-competitive power supply to communities in rural and remote areas, especially in those areas where grid extension is not a cost-effective option. Furthermore, mini grids avoid the problems derived from the instability of the national grid, which in the case of the Tanzanian grid are significant. On average, there are 9.1 outages every month [59], with a mean repair time of 12 hours [60]. Mini-grids can be connected to the main grid or operate independently, and they can provide different levels of services, from basic services of households to satisfying the demand of industrial consumers.

Therefore, mini grids, especially the ones powered by a renewable energy source represent an opportunity to promote social and economic development in the country. Biomass powered mini-grids are still a relatively unexploited solution, mainly due to the issue of seasonality that affects the resource availability.

The three proposed scenarios for the load of the villages will be studied to assess their viability. In all three scenarios the load of the estate will be stable, whereas the load of the villages will be modified accordingly to the changes in each scenario.

The investment in this scenario also includes the cost of the CHP unit for producing the electricity. A funding of 500 USD per every new connection was also considered [49]. The number of new connections was calculated based on the current electrification rate found during the household interviews (24%). The rest of the parameters for the economic analysis are presented in the table below:
The economic results for the three scenarios are compared in Table 18. In the first two scenarios the power consumption of the villages is too low, and as a result most of the power remains unutilized. The NPV by the end of the lifetime of the project is negative, and the payback period is higher than the assumed lifetime. Therefore, it can be concluded that this two scenarios are not feasible from an economical point of view.

In the last scenario almost all of the excess power is used by the villages. This is because the productive uses, that promote the development of the agricultural production in the villages adjacent to the estate, are highly energy intensive. As a result, the investment cost would be recovered by the year 10. However, it is unclear whether or not the villagers would be able to afford the increase in the electricity bill. Therefore, the social acceptability of this scenario could be a threat to its implementation.

![Table 17. Economic parameters of the mini grid scenario](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capital cost</td>
<td>1,227,183 USD</td>
</tr>
<tr>
<td>Electrification funding</td>
<td>365,750 USD [49]</td>
</tr>
<tr>
<td>Number of potential costumers</td>
<td>950</td>
</tr>
<tr>
<td>Electricity tariff</td>
<td>0.128 USD/kWh [58]</td>
</tr>
</tbody>
</table>

Table 17. Economic parameters of the mini grid scenario

![Table 18. Results of the three mini-grid scenarios](image)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total village consumption [MWh/yr]</th>
<th>NPV [USD]</th>
<th>Payback [yrs]</th>
<th>LCOE [USD/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic services</td>
<td>364.75</td>
<td>-557,936</td>
<td>24</td>
<td>0.92</td>
</tr>
<tr>
<td>Evening services</td>
<td>453.83</td>
<td>-351,604</td>
<td>20</td>
<td>0.80</td>
</tr>
<tr>
<td>Productive uses</td>
<td>1,348.89</td>
<td>522,217</td>
<td>10</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 18. Results of the three mini-grid scenarios
Figure 20. Discounted cash flow of the three mini grid scenarios
7.9. Fed into main grid

Another option is to feed the electricity directly into the grid. By signing a Power Purchase Agreement with the DNO (TANESCO), a stable feed-in tariff is guaranteed throughout the lifetime of the project. Therefore, it is the safest and simplest option. Furthermore, the feed-in tariffs for biomass projects are the highest ones among the renewable energy sources. For projects up to 400 kW, which is the case of the biogas power plant, the established tariff is 0.161 USD/kWh [57], which is over 25% higher than the power tariff, which has been assumed to be the tariff in the minigrid scenario.

Due to the high availability of power, the minimum requirement for interconnection, 200 kW, is reached already by year 4, which is when the sale of electricity is expected to start. As a result, the NPV of the project by the year 15 is higher; over 1,513,897 USD, and the investment would be recovered in less than 9 years.

Additionally, as the decorticator represent a big share of the power consumption of the estate, substituting the current, 70-year-old decorticator with a new model could potentially increase the amount of electricity available to be sold to the grid. This efficiency measure was analysed to study its cost-effectiveness. According to Nerini et al., substituting the current 70-year-old decorticator machine with a new one could increase the efficiency by 25% and would have an investment cost of 160,000-200,000 USD [28].

It was found that the NPV of the project would be slightly lower, 1,373,339 USD, whereas the payback period would remain the same, close to 9 years. This is because the amount of electricity available increases only slightly, and, the sale of power to the grid cannot begin before year 4. Therefore, the extra sale of power to the grid will not be enough to compensate for the investment cost of the decorticator.

Figure 21. Discounted Cash Flow of the main grid scenario
8. Impact assessment

8.1. Social impact

During the construction phase, the social impact of the project will be positive, since it would promote the purchase of local materials and the creation of local employment, of both skilled and unskilled labour, even though most of the jobs would be temporary. Furthermore, it would promote the training and education of labour.

During the operation of the plant, it has the potential of promoting the sisal industry, thus benefiting the local communities, particularly sisal harvesters, outgrowers and estate workers. If the digestate is used locally as a fertilizer it could lead to more nutritious and abundant food production as well.

The use of traditional cooking fuels (biomass) has a negative impact on the environment, by causing deforestation, land degradation, soil erosion and associated flooding among other issues [34]. Furthermore, it is detrimental for the health of the people that inhale the indoor air in poorly-ventilated households where biomass is used as a cooking fuel. As the results of the interviews suggest, the local villagers are not satisfied with the current cooking fuel and are willing to change if provided with a better alternative. Having access to modern cooking fuel has the potential of significantly improving the quality of life of the rural populations, and after learning about the potential supply of biogas and the equipment that they would have to purchase, the villagers reacted in a positive way.

Another way of improving the quality of life of the local communities is by supplying the generated electricity through a mini-grid, especially if this means that the households can increase their energy consumption, for example in order to promote agricultural production. Furthermore not relying on the national grid for their power needs would avoid the problems related to the continuous blackouts and brownouts that threaten the social and economic development.

Finally, feeding the surplus electricity to the national grid would provide support to the Tanzanian energy system, which currently experiences a capacity shortage both locally (the north) and nationally. This way, the electricity generated using sisal would help reduce the constant power shortfalls in the country and make the electricity supply more stable and reliable.

8.2. Environmental impact

The reduction in the emissions from the project will come from two sources. On one hand there is a reduction by managing the waste that is currently left in the field without any kind of management. On the other hand, using electricity generated from agricultural waste is less polluting that using other sources, such as diesel fuel, or electricity coming from the grid. Both reductions will be calculated here.

8.2.1) Methane Emission reduction from waste management

The estimation of the reduction in the level of emissions caused by the anaerobic digestion is done based on the emissions of the baseline scenario (i.e. current disposal of the waste in disposal sites, which then undergoes anaerobic decomposition, emitting methane into the atmosphere). The emission reduction is calculated using the CDM methodology AMS-III.AO "Methane recovery through controlled anaerobic digestion":

\[ BE_{CH4_y} = \varphi \cdot (1 - f_y) \cdot GWP_{CH4} \cdot (1 - OX) \cdot \frac{16}{12} \cdot F \cdot DOC_f \cdot MCF \cdot W \cdot DOC_w \cdot e^{-k(y-x)} \cdot (1 - e^{-k}) \]

Equation 2. Calculation of emissions reduction based on baseline emissions [61]

Where:

\( BE_{CH4_y} \) Baseline methane emissions occurring in year \( y \) generated from waste disposal during a time period ending in year \( y \) [t CO\(_2\)eq/yr]

\( \varphi \) Model correction factor

\( f_y \) Fraction of the methane captured at the SWDS in year \( y \)

\( GWP_{CH4} \) Global Warming Potential of CH\(_4\) [t CO\(_2\)eq/t CH\(_4\)]

\( y \) Year of the crediting period for which methane emissions are calculated

\( x \) Years in the time period in which waste is disposed extending from the first year in the time period (\( x = 1 \)) to year \( y \) (\( x = y \))

\( W \) Amount of solid waste disposed or prevented from disposal in the year \( x \) [t]

\( OX \) Oxidation factor (reflecting the amount of methane from that is oxidized in the soil or other material covering the waste)

\( F \) Volume fraction of methane gas recovered

\( DOC_f \) Weight fraction of degradable organic carbon (DOC) in the waste type \( j \)

\( MCF \) Methane Correction Factor

\( DOC_w \) Weight fraction of DOC that decomposes under the specific conditions occurring in the SWDS for year \( y \)

\( k \) Decay rate for the waste [1/yr]

The methodology also suggests default values for some of the parameters in the equation:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi )</td>
<td>0.85</td>
</tr>
<tr>
<td>( OX )</td>
<td>0</td>
</tr>
<tr>
<td>( DOC_f )</td>
<td>0.5</td>
</tr>
<tr>
<td>( MCF )</td>
<td>0.4</td>
</tr>
<tr>
<td>( F )</td>
<td>0.5</td>
</tr>
<tr>
<td>( DOC_w )</td>
<td>40%</td>
</tr>
<tr>
<td>( k )</td>
<td>0.045</td>
</tr>
<tr>
<td>( f_y )</td>
<td>0</td>
</tr>
<tr>
<td>( GWP_{CH4} )</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 19. Default values for the parameters in Equation 2 [61]

Introducing in equation 1 the default values proposed by the methodology and the amount of sisal waste produced gives as a result the amount of CH\(_4\) emissions in the baseline scenario, 702 tonnes
per year. It is assumed that the project will not produce any CH$_4$ emissions onsite: therefore, the amount of emissions for the baseline scenario can be assumed to be the emission reduction of the project.

8.2.2) Estimation of emissions reduction based on electricity generation

Using the biogas to generate electricity has the potential to reduce two sources of emissions. On one hand, part of the electricity will be used to replace the diesel generator, therefore reducing overall CO$_2$ emissions. On the other hand, if electricity is exported to the national grid the CO$_2$ that could have been emitted if fossil fuels were used is avoided.

If biogas is used to generate electricity, and this electricity is then used to process the sisal, the 30,000 litres of diesel fuel that are currently being used per year for the generator would not be required. Using an emission factor for diesel (stationary combustion) of 2.68 kg CO$_2$eq/l [62], it is estimated that the diesel generator emits around 70 t CO$_2$eq/yr. These emissions can be avoided if electricity is produced using biogas.

If part of the electricity is also exported to the grid, methodology AMS-I.D “Grid connected renewable electricity generation” can be followed to estimate the emissions of the power plants displaced due to the project activity. This methodology is based on the following equation:

$$BE_y = EG_{PJ,y} \cdot EF_{grid,y}$$

Equation 3. Calculation of baseline emissions of plants connected to the grid [63]

Where;

$BE_y$ Baseline emissions in year $y$ [t CO$_2$]

$EG_{PJ,y}$ Quantity of net electricity that is produced and fed into the grid as a result of the implementation of the project activity in year $y$ [MWh]

$EF_{grid,y}$ Combined margin CO$_2$ emission factor for grid connected power generation in year $y$ [t CO$_2$/MWh]

It was estimated that 2,340 MWh of electricity would be generated yearly using cogeneration. Some of this electricity would be used internally for the biogas plant and the sisal production, and some of it would be supplied to nearby villages using a mini grid. In the end, around 1,500 MWh of electricity are available to export to the grid.

It was estimated that the emission factor for the Tanzanian grid is 0.77 t CO$_2$/MWh[64]. Therefore, exporting the surplus electricity to the grid will save around 1,150 t CO$_2$ per year.

<table>
<thead>
<tr>
<th>Waste management</th>
<th>Emissions avoided [t CO$_2$/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel savings</td>
<td>70.26</td>
</tr>
<tr>
<td>Grid connection</td>
<td>2,573.49</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3,346</strong></td>
</tr>
</tbody>
</table>

Table 20. Summary of the emission reduction potential of the project
The reduction in the CO₂ emissions could also create an additional source of income in the form of carbon credits. This income can be quantified, although the real feasibility of the access to carbon credits is unclear, as Tanzania has been slow in accessing the international carbon finance markets [66]. There are two types of carbon markets, compliance and voluntary. Compliance schemes are aimed at achieving international or national targets for emissions reductions set by policies such as the Kyoto Protocol. This policy classifies Tanzania as a non-Annex I country and as such it is exempt from reduction obligations but able to access carbon finance for low carbon development through the Clean Development Mechanism, with energy projects in rural areas ranked as having the highest priority. The price for Certified Emissions Reductions (CERs) under this CDM has been volatile as a result of fluctuations in buyer demand and the perceived risk of individual projects, and it usually comes from a negotiation between the project developer and carbon credit purchaser. Furthermore, CDM financing requires that the profitability of the project is lower than 15%, which has hindered the development of projects where investors require higher profitability levels due to higher market or regulatory risks, for example. As a result, regulatory markets are not well developed in Tanzania [66]. For a reference, the selling price

Voluntary markets, however, have increased their presence in the past years. In these markets there is an opportunity for small and medium-sized companies to benefit from carbon credits. As for the price of CERs under voluntary programs, it has been very susceptible to economic recession, but biomass projects are one of the ones with the highest prices due to their high costs of production. The value of voluntary credit of these projects is set at around 12.3 USD/tCO₂eq, higher than the average price in Africa, 5.2 USD/tCO₂eq, but still 50-75% lower than under the regulated market [66]. Promoting and developing regulatory markets in Africa might allow these countries to access the major markets (such as the EU) in the future, which could turn into a bigger presence of CDM projects and higher prices.

Assuming the average price of carbon credits for biogas projects stated above. The following table sums up the emissions reductions for each scenario proposed and the variation in the economic feasibility of the project as a result of the sale of carbon credits:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Emission avoided [tCO₂eq/yr]</th>
<th>New NPV [USD]</th>
<th>Variation in NPV</th>
<th>New Payback Period [yrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas for cooking</td>
<td>1,464</td>
<td>-151,988</td>
<td>+42%</td>
<td>18</td>
</tr>
<tr>
<td>Biogas+ main grid</td>
<td>3,856</td>
<td>1,863,157</td>
<td>+18%</td>
<td>8</td>
</tr>
<tr>
<td>Mini grid - basic services</td>
<td>1,040</td>
<td>-481,322</td>
<td>+14%</td>
<td>23</td>
</tr>
<tr>
<td>Mini grid – evening services</td>
<td>1,178</td>
<td>-264,783</td>
<td>+33%</td>
<td>19</td>
</tr>
<tr>
<td>Mini grid- productive uses</td>
<td>1,811</td>
<td>655,699</td>
<td>+26%</td>
<td>9</td>
</tr>
</tbody>
</table>
The results of the analyses show that selling the carbon credits would improve the economic results of all the scenarios, especially for the scenario where all of the biogas is used for cooking, improving the NPV by almost 42%. Nevertheless, the project still remains unprofitable. It was found that the projects that were not profitable before will still remain so even with the additional income from the sale of carbon credits. The scenarios that were profitable before will also increase the profitability and reduce the time needed to recover the investment by 1 year. This reduction in the payback period can help the acceptability and implementation of the project.

However, due to the reduced presence of Tanzanian projects in carbon markets in the past it is unclear whether including this extra income in the economic analysis is realistic.

8.2.3) Water use

Sisal does not require irrigation for growing. However, processing the leaves is a very water intensive process. On average, 100 m³ are needed to process one tonne of fibre [65]. Installing an AD plant may facilitate water recirculation, reducing the need for fresh water for decortication.

8.2.4) Water pollution

The environmental impact from the liquid fraction of the SDR would also be clearly reduced, facilitating compliance with recent regulation and improving the water quality downstream of the plantation.

Discarding the sisal waste can lead to water pollution. Treating the sisal pulp and wastewater will thus directly benefit the environment. However, it might have a negative impact on the households downstream of the plant that use the wastewater for irrigation due to its nutrient content. Currently, the villagers use the water from the sisal plant for irrigation due to its nutrient content, which enhances the plant growth in fields downstream of the plant. Drinking water is taken from upstream of the sisal plant. However, due to possible penalties by the Government (up to 5,000,000 TZS every 6 months) based on the non-compliance with environmental statutory requirements, the Estate is constructing a facultative pond that will store the process water, which will later be used for irrigation purposes at the estate. Therefore, the villagers will no longer have access to this water and the project will have a negative impact on the agricultural yield for the villagers.

8.3. Technology transfer

Lack of technical knowledge and training is one of the barriers to the diffusion of biogas technologies in Sub-Saharan Africa [34]. A better comprehension of available technology and its benefits for the rural populations might lead to an increasing presence of biogas plants in the region.

If the project is successful, it will lead to a deeper understanding of the funding possibilities, construction, operation and maintenance. As a result, this might lead to the replication of similar solutions both locally and nationally.
9. Scenario comparison

After analyzing the scenarios separately, the obtained results can be compared. First, the economic parameters under study are summarized in Table 22:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NPV  [USD]</th>
<th>Payback [yrs]</th>
<th>LCOE  [USD/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas for cooking</td>
<td>-246,325</td>
<td>19</td>
<td>0.58</td>
</tr>
<tr>
<td>Biogas + main grid</td>
<td>1,578,986</td>
<td>9</td>
<td>0.25</td>
</tr>
<tr>
<td>Mini grid- basic services</td>
<td>-557,936</td>
<td>24</td>
<td>0.92</td>
</tr>
<tr>
<td>Mini grid- evening services</td>
<td>-351,604</td>
<td>20</td>
<td>0.80</td>
</tr>
<tr>
<td>Mini grid- Productive uses</td>
<td>522,217</td>
<td>10</td>
<td>0.50</td>
</tr>
<tr>
<td>Main grid</td>
<td>1,513,897</td>
<td>9</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 22. Results of the economic analysis of the scenarios

Based only on the economic study it can be concluded that the two most profitable scenarios are combining the supply of biogas for cooking purposes and electricity sales to the main grid and the sale of all the available power to the national grid. For both of these scenarios the NPV by the end of the project lifetime is higher than 1,500,000 USD, and the time needed to recover the investment is lower than 10 years. There is only one more scenario with a positive NPV: the construction of a mini grid where sufficient power is supplied to promote productive uses in the surrounding villages.

Out of these three scenarios, the mini grid is the least safe option, since it relies on the assumption that the villages want, and can afford, the increase in the electricity consumption. Furthermore, the results from the interviews suggest that the households don’t see the increase in their electricity consumption as a priority. The main grid scenario is safer, as the benefits come from a contract between the company and the national DNO, and therefore are not dependent on the social acceptability. As for the sale of biogas, it is likely that households will be willing to pay for the cooking fuel, not only because the interviews indicate so, but also because it would not represent an increase in the amount of money spent in cooking fuel compared to the current situation.

Finally, looking at the other two dimensions of sustainability, both of these projects would have a positive impact on the environment. In both cases the amount of diesel used at the estate would be significantly reduced, and the emissions derived from the lack of waste management, avoided. In the case of the biogas scenario it would also mean the replacement of polluting, traditional cooking fuels, with a cleaner option. If all the excess power is fed into the main grid it would replace part of the electricity that is currently being generated using mainly fossil fuels. The overall emission reductions of both scenarios are compared in the table below:
The emission reduction is slightly larger in the biogas scenario, and therefore it can be concluded that this scenario is more favorable from the environmental point of view. As for the social perspective, for the reasons stated earlier in this report, having access to a more efficient and cleaner cooking fuel could significantly improve the quality of life of the villagers, whereas the scenario where all the excess power is fed into the main grid has no direct social impact, other than the creation of new jobs and the increase in the value of sisal, but these benefits will also exist in the other scenarios.

Therefore, the more sustainable scenario, meaning the one with that maximizes economical, social and environmental gains is to supply part of the biogas to the households under a 2 km radius for its use as a cooking fuel and feed the rest of the produced power directly into the main grid.

### 10. Concluding Remarks

The implementation of renewable energy projects in developing countries contributes to poverty alleviation, provides energy services in remote location where access to the main grid is not economically feasible and promotes social development. However, for these projects to be successful they need to be developed taking into account the local context and conditions.

In the case of Tanzania, the unstable energy supply and low electrification rates are two obstacles hindering the social and economical development of the country. It has been stated that the solution to the energy problem in Tanzania needs to include better management and additional generation. Because of its agricultural-based economy, there is a high potential for the use of agricultural residues for energy generation in the country. In that context, this thesis studies the potential use of the residues generated at Mkumbara Sisal Estate. The results of the study show that by managing the sisal residue it is possible to meet the demand of the sisal estate itself, and still generate enough excess power for its use in other applications.

Some of these potential applications were analysed in this report as a series of scenarios, out of which it was found that the solution with the most favourable outcomes would be a combination of biogas sale to the surrounding villages and electricity sale to the national grid. This solution will benefit the owner of the estate, which would not have to depend on the unreliable national energy supply to meet the demand of the decortication of the sisal, which is a highly energy intensive process. The project would also be profitable for the company, since the investment would be recovered in less than 9 years and therefore would suppose an additional source of income for them. The surrounding local populations would also benefit from the project, as their quality of life would significantly improve by having access to modern cooking fuels, which could reduce the presence of diseases and avoid the time-consuming activities associated with the use of traditional biomass fuels. Finally, the projects would potentially lead to a significant reduce in the CO₂ emissions, therefore improving the sustainability in all its dimensions.
11. Future work and recommendations

There are several matters that have not been addressed in this thesis but would provide a better insight into the generation of energy services from sisal residue. One example is the potential sale of the generated heat, which in this report has been assumed to be used only for heating up the digester. Potential customers for this heat could be industrial centers in the area.

Another product of the biogas plant which has not been discussed is the digestate. Future studies should look into the potential sale of the digestate as fertilizer to local customers, or its use inside the estate.

As biogas technologies can work with different substrates, there is also potential for co-digestion using other agricultural residues or other types of waste, such as animal manure. Additionally, the energy production could be increased by combining the biogas with other renewable energy sources. Solar technologies are particularly interesting in African countries.

Finally, the replicability of the project should also be assessed. There are other rural areas in the country that could also benefit from the anaerobic digestion of agricultural residue, particularly of sisal residues, as estimated by Kivaisi and Rubindamayugi [30].

12. Acknowledgements

The author would like to express their acknowledgement to the following people, who have significantly contributed to the completion of this master thesis:

I would like to express my deepest appreciation to the company Renetech, for the opportunity of being part of this project and to participate in the trip to Tanzania. Especial thanks to my supervisors in the company, David Bauner and Tom Walsh, for their valuable technical support and constructive suggestions, as well as their guidance throughout the field work. And to my colleague, Iqlima Fuqoha, for the support and valuable contributions during these six months, particularly during the field work.

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Finally, I would like to extend my thanks to my supervisor at KTH, Shahid Hussain Siyal, for his guidance and advice throughout the work.
13. References


[27] Leo Oudshoorn, “Biogas from sisal waste,” Eindhoven University of Technology, Faculty of Philosophy and Social Sciences.


Appendix

A. Template for household questionnaire

1. Number of members:
   a. Female: _____
   b. Male: _______

2. Amount of monthly income of the household: ________ TZS

3. Main source of income:

4. Priorities for income expenditure (ranking 1-6; 1 being the most important):

<table>
<thead>
<tr>
<th>Item</th>
<th>Ranking</th>
<th>Amount of money spent per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clothes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Health services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Amount of fuel used for cooking in the household:

<table>
<thead>
<tr>
<th>Type of fuel</th>
<th>Kerosene (liter)</th>
<th>Biogas (m³)</th>
<th>LPG (m³)</th>
<th>Firewood (kg)</th>
<th>Dung (kg)</th>
<th>Charcoal (kg)</th>
<th>Coal (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount consumed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. Type of stove used:

7. If biomass is used, is it collected or bought?

8. How difficult is it have access to the cooking fuel? (mark with X)

<table>
<thead>
<tr>
<th>Very easy</th>
<th>Somewhat easy</th>
<th>Very difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9. Level of satisfaction with current cooking fuel (from 1 to 10, 1 being completely unsatisfied and 10 completely satisfied): ______

10. Will you be willing to change the way you cook today (Yes/No)? ______ If “yes”, specify reason(s) why:

11. Will you be willing to use biogas from agricultural waste for cooking your food (Yes/No)? ______

12. Type and number of appliances consuming electricity in the household:

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Number of appliances</th>
<th>Power [W]</th>
<th>Hours usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light bulbs Type:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fridge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile phone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump/motors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13. Average monthly electricity consumption of the household: ______kWh

14. Source of drinking and cooking water (tap water, own well, community well, river...): ______

15. Agricultural crops in the household and cultivation period:

16. Do you own any livestock? (Yes/No): ______

17. Has any household members suffered any common diseases associated with cooking fuel (Asthma, Tuberculosis, Eye disease, Pneumoconiosis, Skin disease, Acute Respiratory Infections, Burn)? (Yes/No): ______

18. Has any household members suffered any common diseases associated with water? (Skin disease, Diarrhea, Numbness in the hands and feet, black and weak teeth and nails)? (Yes/No): ______
Biogas is the gaseous product of breaking down organic matter in the absence of oxygen. It is a mixture of mainly methane (50-70%) and carbon dioxide. At household level, biogas systems can be used to produce fertilizer and for providing energy for cooking transporting the produced gas through piping system from the plant. Cooking on biogas is faster and easier than cooking on charcoal or firewood. It keeps your kitchen clean and tidy, and protects your family from the dangers of indoor air pollution.

Example of biogas for cooking appliances products from SimGas:

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of Appliances</th>
<th>Details Info</th>
<th>Retail Price/unit (TZS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Single burner stove</td>
<td>- Durable Stainless steel body</td>
<td>40,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Die-casting burner with stainless steel cover</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Heat power: 3.2 kW with gas consumption of 0.8 m³/h</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Double burner stove</td>
<td>- Durable Stainless steel body</td>
<td>75,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Die-casting burner with stainless steel cover</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Heat power: 3.2 kW with gas consumption of 1.4 m³/h</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Biogas rice cooker</td>
<td>- Corrosion free stainless steel body with aluminum inner pan &amp; steamer</td>
<td>75,000</td>
</tr>
<tr>
<td>4.</td>
<td>Biogas pressure gauge</td>
<td>- Plastic design to prevent the corrosion from the biogas</td>
<td>5,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Easy connecting design</td>
<td></td>
</tr>
</tbody>
</table>
### B. Breakdown of the investment cost of the biogas plant

#### Equipment

<table>
<thead>
<tr>
<th>Item</th>
<th>Size</th>
<th>Total cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding tank</td>
<td>300 m³</td>
<td>12,916.54</td>
</tr>
<tr>
<td>Hydrolysis tank</td>
<td>550 m³</td>
<td>23,680.33</td>
</tr>
<tr>
<td>Main digester</td>
<td>2,050 m³</td>
<td>88,261.10</td>
</tr>
<tr>
<td>Post digester and membrane roof</td>
<td>4,400 m³</td>
<td>189,438.46</td>
</tr>
<tr>
<td>Digestate/fertilizer pond</td>
<td>1,250 m³</td>
<td>53,819.02</td>
</tr>
<tr>
<td>Tank cover</td>
<td>700 m²</td>
<td>25,833.82</td>
</tr>
<tr>
<td>Digester technical equipment</td>
<td></td>
<td>163,552.10</td>
</tr>
<tr>
<td>Control room</td>
<td></td>
<td>203,082.05</td>
</tr>
<tr>
<td>Feeding tank technical equipment</td>
<td></td>
<td>38,722.00</td>
</tr>
<tr>
<td>Transport costs</td>
<td></td>
<td>5,534.82</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>804,840.24</strong></td>
</tr>
</tbody>
</table>

#### Construction costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Size</th>
<th>Total cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground excavation</td>
<td>2000 m³</td>
<td>4,304.98</td>
</tr>
<tr>
<td>Labour construction</td>
<td>10 people</td>
<td>25,829.04</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>30,134.02</strong></td>
</tr>
</tbody>
</table>

#### External services

<table>
<thead>
<tr>
<th>Item</th>
<th>Total cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervision, commissioning and training</td>
<td>41,996.83</td>
</tr>
<tr>
<td>Planning, engineering and advice</td>
<td>25,982.91</td>
</tr>
<tr>
<td>Other costs</td>
<td>196,951.38</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>264,931.12</strong></td>
</tr>
</tbody>
</table>
C. Equations for the economic analysis

- Simple cash flow

\[ CF = \sum_{t=1}^{T} Revenues_t - O&M costs_t \]

Equation 4. Simple cash flow

Where

\( CF \)  
Cash Flow

\( t \)  
Year

\( T \)  
Project lifetime

\( Revenues_t \)  
Sum of revenues during year \( t \)

\( O&M costs_t \)  
Sum of operational costs during year \( t \)

- Discounted cash flow

\[ DCF = \sum_{t=1}^{T} \frac{CF_t}{(1 + r)^t} \]

Equation 5. Discounted Cash Flow

Where

\( DCF \)  
Discounted Cash Flow

\( t \)  
Year

\( T \)  
Project lifetime

\( CF_t \)  
Simple cash flow for year \( t \)

\( r \)  
Discount rate

- Net Present Value

\[ NPV = DCF - C_0 \]

Equation 6. Net Present Value

Where

\( NPV \)  
Net Present Value

\( C_0 \)  
Capital investment