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Feasibility Study of Hybrid Renewable Energy Systems Mini-Grids for Rural Communities in Mali: Case Study Sokolo

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Feasibility Study of Hybrid Renewable Energy Systems Mini-Grids for Rural Communities in Mali: Case Study Sokolo

By:

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Bsc. Thermal Engineering and Renewable Energies

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MASTERS OF SCIENCE, ENERGY ENGINEERING TRACK

August, 2018

DECLARATION

I, Safiatou Mariko, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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Abstract

Despite the efforts made so far in developing countries, access to energy and electricity remain a challenge especially in Mali, particularly in remote rural areas. Mali is endowed with good renewable energy potential, such as hydropower, solar energy, wind energy, and biomass from agricultural residue. In this study various options of hybrid (renewable) energy system using the available renewable energy resources for electricity are designed from rural electrification perspective. This study assesses the feasibilities of hybrid renewable power systems for the Sokolo community in Mali. The Hybrid Optimization Model for Electric Renewable (HOMER) software was used to run the technical and economic analyses. The feasible system design for the village of Sokolo's load (biogas generator/ solar PV modules / storages batteries /converter) was found to compose of 100 kW of solar PV array, 150 kW biogas generator, 109,060 Ah batteries and 30 kW of converter/inverter to meet a total load of 610 kWh/day and a peak load 136.71 kW .The hybrid renewable energy power system has levelized cost of energy (LCOE) of US$ 0.279 /kWh, a net present cost (NPC) of US$ 804,174, a CO_2 emission of 490 kg/yr, a simple payback time of 8 years and a renewable energy fraction of 100%. The selected system was compared to the scenario used by AMADER (Malian agency for domestic energy and rural electrification) of diesel generator/ solar PV modules/ storage batteries/converter which has a lower LCOE and NPC for supplying the same load at US$ 0.323 /kW and US$ 930,883.3 respectively. In addition sensitivity analysis is performed to consider uncertainty in variables: biomass price, PV equipment (modules, batteries, converter, and inverters) and biogas generator price multiplier on the NPC and the LCOE of the selected system.

Résume

Malgré les efforts déployés jusqu'ici dans les pays en voie de développement, l'accès à l'énergie et à l'électricité reste un grand défi, spécialement au Mali, et en particulier dans les zones rurales reculées. Le Mali dispose d'un bon potentiel de ressources énergétiques renouvelables, telles que l'énergie hydraulique, l'énergie solaire, l'énergie éolienne et la biomasse provenant de résidus agricoles. Dans cette étude, diverses options de système énergétique hybride (renouvelable) utilisant les ressources énergétiques renouvelables disponibles pour l'électricité sont conçues du point de vue de l'électrification rurale. Cette étude évalue les possibilités de systèmes hybrides à énergie renouvelable pour la communauté de Sokolo au Mali. Le logiciel d'optimisation hybride pour les énergies renouvelables électriques (HOMER) a été utilisé pour effectuer les analyses techniques et économiques. La conception du système réalisable pour la charge du village de Sokolo (générateur de biogaz / modules photovoltaïques solaires / batteries d'accumulateurs / convertisseur) s'est avérée composée de 100 kW de panneaux photovoltaïques, d'un générateur de biogaz de 150 kW, de batteries de 920 Ah et d'un convertisseur / onduleur de 30 kW pour répondre à une charge totale de 610 kWh / jour et une charge de pointe de 136,71 kW. Le système d'énergie hybride à énergie renouvelable a nivelé le coût de l'énergie à 0,279 dollar EU / kWh, soit un coût net de 804 174 dollars American. Une émission de CO2 de 490 kg / an, un retour sur investissement simple de 8 ans et une fraction d'énergie renouvelable de 100%. Le système retenu a été comparé au scénario utilisé par l'AMADER (agence malienne pour l'énergie domestique et l'électrification rurale) des générateurs diesel / modules photovoltaïques / accumulateurs / convertisseurs ayant un LCOE et des NPC inférieurs pour fournir la même charge à 0,323 USD / kW et 930 883,3 dollars respectivement. En outre, une analyse de sensibilité est effectuée pour tenir compte de l'incertitude liée aux variables: prix de la biomasse, des équipements solair (modules, batteries, convertisseur et onduleurs) et de l'augmentation de prix du générateur de biogaz sur le NPC et le LCOE du système sélectionné.

Acknowledgement

My sincere gratitude goes first to the almighty God for giving me guidance, protection and strength to lead this project to the end, for its benefits throughout my life and my undertaking. A profound gratitude to my parents for their help and their guidance.

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CHAPTER 1

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1. INTRODUCTION

1.1 Context

The supply of clean, reliable and affordable energy in a secure, sustainable and environmental friendly way is an important precondition for economic, social and industrial development of a nation and the well-being of its population. In 2016, about 1.1 billion people around the world did not have access to electricity, most of whom lived in remote rural areas of Sub-Saharan Africa (IEA, 2017). Efforts toward universal electrification access have been stepped up in the region leading to the decrease of the number of people without access in the region. Despite all the best efforts, electrification rate in the region is currently at 43%. Universal access to electricity is the core of many of the ambitious the new United Nations sustainable development golds SDGs to be met by 2030 and Africa’s Agenda 2063 (the Africa we want through long-term planning, a set of goals and targets to ensuring access to modern, efficient, reliable, cost-effective, renewable and environmentally friendly to all while harnessing all its energy resources, central issues consider by PAUWES research Agenda. With the 17 SDGs being interconnected, it is believed that achieving one will have tremendous effect on the others, including access to energy, reducing waste, combating climate change and halting deforestation. Renewable energy sources play major role in achieving electricity access in both grid-based electrification and the expansion of decentralized technologies that are essential for remote rural areas. Wind, Solar PV, and hydropower dominate in this market. Renewables comprised an estimated 27.7% in 2014 (Sawin et al., 2016) of the world’s power generating capacity, enough to supply an estimated 22.8% of global electricity.

Currently there is a 10% annual growth in Mali’s electricity demand (BAD, 2010). This presents a veritable challenge to the government and the national electricity utility operators ‘Energie du Mali’ (EDM) in reducing imports of fossil fuels, as well as to the nation, and to private investors in providing sufficient electricity at reasonable prices. A lot of work has been done in Mali in the purpose of mapping renewable energy resources and assessing the potential agricultural residue for energy production in Mali. (Nygaard, et al 2012) has done an assessment of the main agricultural residue available for electricity production. Cotton and rice were the two most promising crops considering the total amount and the concentration of production (Risø-R-Report, 2012). Pre-feasibility study for an Electric power plant based on rice straw using modeling, satellite images and existing global datasets for rapid preliminary assessments of renewable energy resources has been done in Mali (Nygaard et al., 2012a). Most of the studies (the feasibility of a power plant working with the rice husks from agricultural residue) were done in purpose of achieving national access to electricity and in rural areas (rural electrification). Most of the current rural electrification projects in Mali which is under the responsibility of The Malian Agency for the Development of Domestic Energy and Rural Electrification (AMADER) looks at achieving rural electricity access using solar and diesel hybrid systems, thus dependent of fossil fuels.

Access to electricity in rural areas has gone up from 1% in 2000 to about 20% (AMADER, 2016). The overall electrification rate for Mali is 34.8% (SE4ALL, 2015), however many of these achievements was done through diesel driven mini-grids that often are not truly operational because of high fuel prices. Mali being an agricultural region generated significant crop residues that could be used for electricity production. From literature the agricultural residues in Mali are used for animal feed, some as soil fertilizer and the remainder is burned in the field. The burnt portion represents a major biomass potential which could be used in the production of electricity also from recent studies a significant amount of the portion incorporated into the soil due to its effect on the soil. Rice is a major produced crop in Mali, with a total production of about 2.92 million tonnes in 2016 (FAO, 2016). Utilization of the rice residue for electricity generation is considered to be economically and sustainably feasible. This thesis will focus on using agricultural residue for electricity generation in off-grid Malian communities.

1.2 State of art

Many Malian rural communities, like other remote villages across the developing world, do not have access to electricity. They rely on other sources of lighting that do not provide enough lumen and are unclean and environmentally unfriendly and release harmful gas in the atmosphere (CO_2 emissions). There has been increased research during the last decade aimed at providing clean and affordable energy to people living in remote areas. Grid extension cost in those areas is often prohibitive. Renewable energy resources present a good option for these remote areas. However, relying on a single renewable energy source (standalone technologies) may not be the best option, as it would increase the need for storage and reliability problems from the selected renewable energy sources (intermittency). Hybrid system (Combining of different resources), where they are available, often present a better solution. (Akikur et al., 2013) compared standalone and hybrid solar energy systems suitability for off-grid rural electrification in which they reviewed technics to reduce the complexity of designing a hybrid renewable energy system HRES. They also presented tools and software that helps in design and optimization of hybrid systems: HOMER (Hybrid Optimization Model for Electric Renewables). This software is the most widely used for purposes of hybrid systems optimization. Analysis with Homer requires input on load data, data on all resources, component types and their specifications, economic constraints and costs, efficiency levels, expected lifetime. According to (Akikur et al., (2013), HRES could became more feasible form the point of view of environment and cost-competitiveness compared to diesel generators in achieving electricity access in remote areas. HRES (solar-wind) compared to wind only and solar only was found to be more cost-effective. It highlights the fact that the large and medium hydropower (> 25 MW) are no more environmental friendly as it results in the creation of large reservoirs that could destroy generative lowlands and river and ecosystems grassland. One the most important and widespread renewable energy resources in Africa and elsewhere in the world is solar energy. As matter of fact it is included in almost every off-grid system for remote areas electrification. (Bhandari et al., 2014) introduced a new off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. To solve the intermittent nature of renewable energies, they proposed the use of storage systems and conventional generators as backup systems to improve the reliability and power quality of those systems. They also emphasized that to be commercially viable, HRES should include PV-battery; PV-diesel, etc. They also studied systems focusing on optimizing HRES with or without backup systems or conventional generators. (Bhandari et al., 2014) presents a PV–wind hybrid system located in Thingan and a micro-hydro power (MHP) located in the Kolkhop village, Makawanpur District, 7 km from Thingan in Nepal. According to the study and the load figure, the systems could not satisfy the demand of the two villages. Hybridizing the two power plants into a single mini-grid increased the reliability of the power supply and satisfied the demand and the process. It even granted the system with sufficient power surplus to charge the storage device during off-peak hours. They concluded that HRES is relatively cost-effective in areas where the national utility grid is expensive and where no grid is available or grid extension would be too costly, making it suitable for power applications in remote areas. Integrating distributed generating systems in a mini-grid increases the reliability and quality of power. Again in an attempt of increasing the energy access in rural communities, (Nfah & Ngundam., 2009) conducted a feasibility of pico-hydro and photovoltaic hybrid power systems for remote villages in Cameroon with an objective to simulate a pico-hydro and solar options that incorporate a biogas generator for electrification purposes in Cameroon's remote villages. The simulation options included pico-hydro/biogas generator/battery systems (Simulation 1) PV/biogas generator/battery systems (Simulation 2) using HOMER. After compilation they found that these options competed favourably with the grid extension and that off-grid options based on HRES could be a suitable alternative for rural electrification in power range of 10-50 kW in Cameroon. (Setiawan et al., 2009) also conducted a study on the design process of a mini-grid hybrid power system with reverse osmosis desalination plant. They looked at the economic analysis and environmental considerations for the project life cycle with the purpose of supplying electricity and fulfilling clean water needs in remote areas by utilising renewable energy sources and a diesel generator with a reverse osmosis desalination plant as a deferrable load. The environmental aspects analysed included the amount of gas emissions such as CO_2 and NO_2 as well as particulate matter released into the atmosphere. They performed simulations using HOMER based on actual conditions in a remote area in the Maldives. One particularly interesting application of renewable energy systems is installation of hybrid energy systems in remote areas, where utility grid extension is either impractical or prohibitively expensive and where the cost of fuel drastically increases with the remoteness of the location (Asrari et al., 2012).

1.3 Research Objective

1.4.1 Main Objective

The main objective of this thesis is to find a suitable, cost-effective, clean and environmentally friendly hybrid renewable energy system (HRES) for people living in Sokolo, a rural community in Mali.

1.4.2 **Specific Objective**

The specific objectives are to:

- Estimate the electricity demand of the community;
- Assess the renewable energy resources in the area that could support the development of a hybrid mini-grid;
- Perform a technical assessment of the hybrid mini-grid to meet the demand estimated above; and
- Perform an economic assessment of the hybrid mini-grid.

1.4 Research hypothesis

Using HRES mini-grid is a more feasible way of supplying clean and affordable energy access to people living in rural areas.

1.5 Research question

- What is the electricity demand of the community?
- Is there enough renewable energy resource in the selected community to support hybrid mini-grid development?
- Is it technically and economically feasible to develop a mini-grid using a combination of the resources found in the selected community to meet their electricity demand?

1.6 Research Methodology

Data collection began with secondary data at the Malian Agency for Rural Electrification (AMADER), the agency in charge of rural electrification, since they have collected a lot of data for many communities in the country with the aim of supplying such communities with clean and affordable energy in the future. This data was supplemented with resource data from the community. The data collection covered solar, wind, biomass and of the community. Data collection for the community considers: current energy access rate in the community, the present energy demand, types of energy in use currently, energy supply sources presently, and the available renewable energy resources available. Data collected was modeled using HOMER, to design, simulate and optimize a hybrid renewable energy system mini-grid.

CHAPTER2

CHAPTER 2

2. LITERATURE REVIEW

2.1 Country presentation

Mali is a large landlocked country in West Africa with 1.24 million square kilometers (480,000 square feet) of land area. It lies between latitudes 10° and 25°N, and longitudes 13°W and 5°E. Mali is bordered by Algeria to the north, Niger to the east, Burkina Faso and Côte d'Ivoire to the south, Guinea to the south-west, Senegal and Mauritania to the west (See Figure 2.1). About 90% of the people in Mali live in the southern region with the Niger and Senegal rivers, far from the Sahara Desert (United Nations Desa / Population Division, 2017). The climate is highly variable and characterized by a long dry season and a rainy season averaging one month in the north and up to five months in the south. Rainfall ranges from 200 mm/year to 1,200 mm/year and has resulted in the climatic stratification of the country into four ecological zones with a highly diversified agricultural potential. Mali is highly vulnerable to climate change, climate variability and desertification. These factors may create risks for (rural energy) RE sector, affecting biomass production and hydroelectric resources. A large part of electricity production comes from large-scale hydropower produced on the Senegal and Niger rivers. Agricultural is the major source of income for more than 80% of the population (AfDB, 2015). The primary energy supply in Mali is biomass, supplying 78% of all energy consumed. As of July 2017 the Malian population accounted for about 17.9 million inhabitants (The World Factbook, 2018) with an average annual growth rate of 3.4%. Majority of the population (about 64%) live in rural areas, but the urban population is growing steadily at 5% per annum. The population is comprised of several sub-Saharan ethnic groups, with Bambara being the largest, accounting for 37% of the population. While the official language of Mali is French, 80% of the people speak Bambara. Electricity access rates are low but improving at 55% in urban and 15% in rural areas in 2015 (REN21, 2015) . Growth in electricity demand is mainly driven by domestic consumers, industrial and the mining sectors (see other details in Table 2.1). The national grid has a large but declining share of hydroelectricity which accounts 44.4 %of all electricity produced in 2014, with the rest from fossil fuel powered plants. Specific domestic energy policies are being addressed by the state and by the rural and domestic energy agency (AMADER, 2014).

Source : ONU

Figure 2.1: Map of Mali

Table 2.1: Key Indicators for Mali 2017

Country name	Mali
Area	1.24 million km^2
Population density	15 persons per km^2
Energy production	2.175 billion kWh
Energy consumption	2.023 billion kWh
Electricity access	31%
CO$_2$ emission form energy consumption	800,000 Mt

2.2 Electricity challenges in Mali

One of the main challenges in achieving electricity access in Mali especially in rural remote areas is the fast growing population with the annual growth rate of 3.4%, the country's low population density of 15 persons per km², the villages are widely dispersed and the main grid has not yet expanded to all major cities. The sector is also sensitive to a high dependence on oil importation with its constant price increase, stressed by demand and economic growth. This also affects local energy service providers in rural areas that operate isolated fossil-fuelled mini-grids. They also are particularly affected by rising and volatile fuel prices as well as considerable fuel transport costs in Mali.(AfDB, 2015)

Most households in rural areas satisfy their electricity needs by using kerosene and batteries, which are expensive and unreliable. The power transmission and distribution system is mainly managed by Energie du Mali SA (EDM), the national utility and local energy service providers operating in public-private partnerships (PPPs) with national agencies in isolated rural areas. The projected expansion of the national electricity grid is unlikely to connect a significant number of isolated low-income populations in the next decade, thus creating a considerable market for isolated off-grid rural electrification schemes.

Climate vulnerability also greatly affects Malian electricity production which depends on hydroelectric power for about 44.4 percent in 2014 in interconnected systems only (AfDB, 2015) of its on-grid electricity supply. Climate change is expected to exacerbate this situation further and to impact biomass production as well. Renewable energy has great potential to address many challenges as well as to contribute to socio-economic development and poverty reduction.

2.2.1 Current status of electricity sector energy sector description

The Malian electricity sector can be divided into four segments: the interconnected system, isolated centers, captive generation by large consumers and the rural sector. Electricity generation is vulnerable to climate variability since a significant portion of the on-grid supply managed by EDM SA comes from hydro power plants 44.4percent of the national production drawn from the two largest rivers of the country, namely the Niger and Senegal, forming immense watersheds (300,000 km^2 for the Niger, and 155,000 km^2 for the Senegal). The total flow potential of these two river systems is estimated at 56,000,000,000 m^3 per year, and the country's estimated hydro potential is nearly 1 GW, as of 2014. Mali is highly dependent on oil imports and given its price volatility has a strong impact on the economy of the country. With climate change–related weather extremes, the security of electricity supply from hydropower and biomass production patterns can be easily threatened in the future (SREP, 2011). Inadequate grid developments make electricity relatively expensive and inaccessible for the majority of the population (SREP, 2011). Small and large-scale diesel generators still provide about 20% of total production. Interconnectors are being planned and built to meet some of the demand though electricity generated from natural gas in Ghana and Ivory Coast (Nygaard et al., 2012). In 2016 the total installed capacity in Mali reached 534 MW. The production is divided in two methods: isolated plants that are small plants for the electrification of some peri-urban location of a few kW capacity, where electricity is generated mainly through solar PV and in some project like YELEN COURA and BAGANI YELEN in Garalo (village in Mali) and other project like them where electricity is provided through diesel generator modified to work on jatropha oil (bio diesel). The plants working on biodiesel from jatropha and the interconnected system, owned and managed by EDM SA, (production dominated by hydroelectricity, mainly generated by the Manantali Dam (of which Mali owns 104 MW out of the total 200 MW) and Sélingué (46 MW) Felou, Sotuba etc.) consist the important share of Malian electricity production See Figure 2.2 and Figure 2.3 (EDM, 2016).

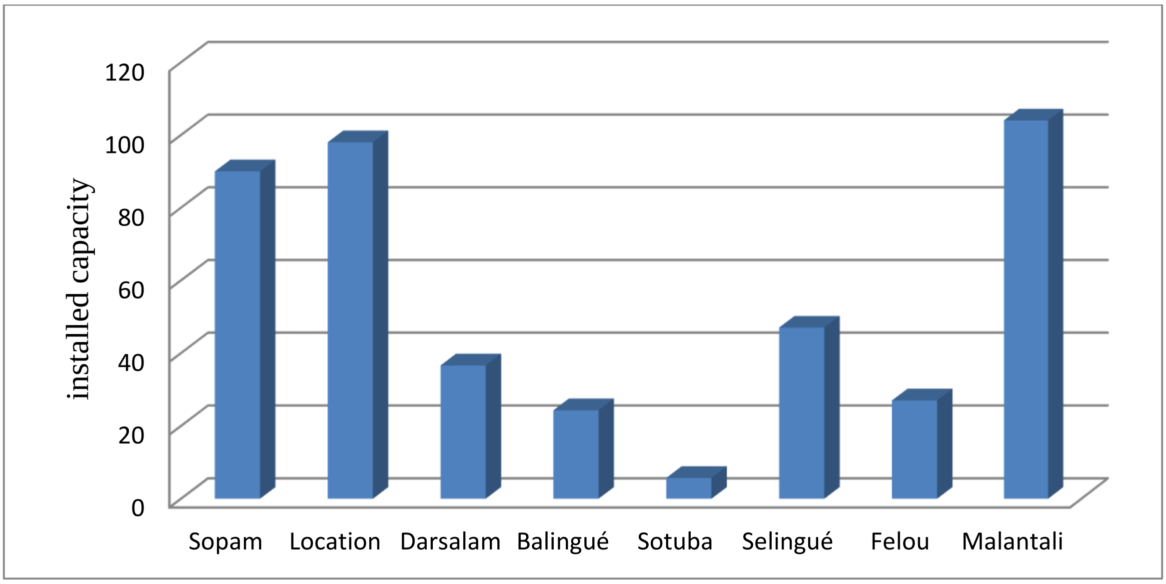

Figure 2.2: Capacity installed in Grid-connected electricity generation plants in 2016

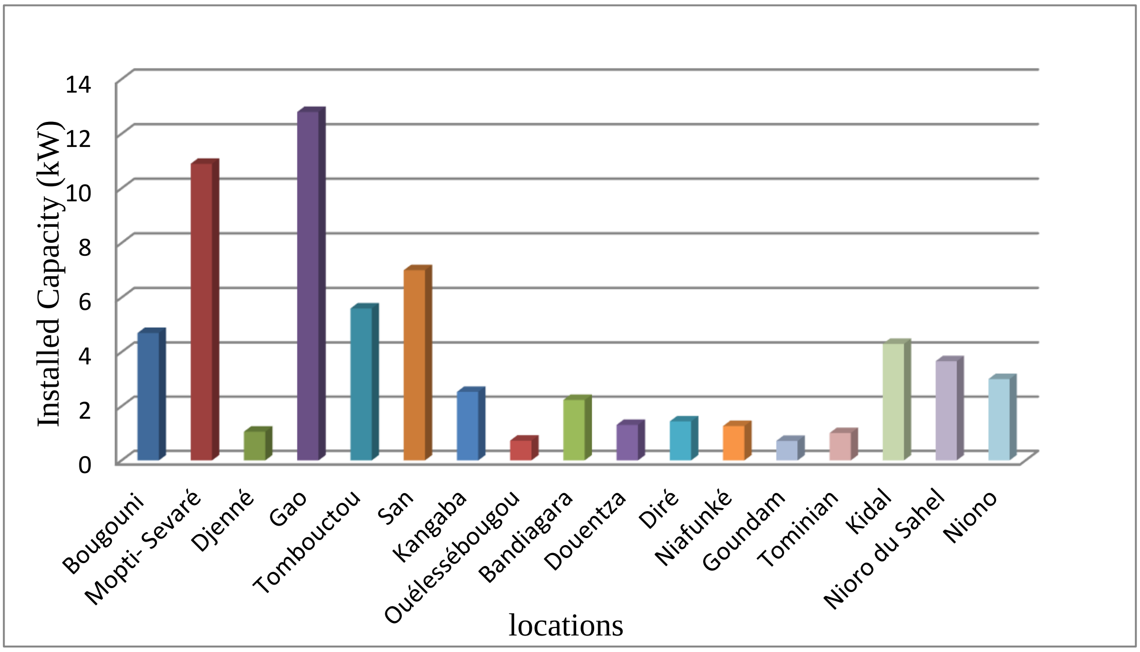

Figure2.3 Off-grid electricity generation plans MW (2016

2.2.2 Electricity transmission and distribution in Mali

The interconnected electricity grid in Mali only reaches a limited area in the central/southern part of Mali (see the full lines in figure 2.4 below). The rest of Mali has no electricity supply or have small generation plants (mainly diesel engines) supplying electricity to the isolated grids (Risø-R-Report., 2012). Mali's Interconnected Network (Resaux interconnecté RI) electricity system serves thirty-two (32) localities including the capital Bamako, twenty-eight (28) Isolated Centers (IC) using decentralized generation and two (2) centers connected to the medium voltage network of Cote d'Ivoire. The grids connected generation feeds Bamako the capital and and some major cities e.g Kati, Koulikoro, Fana, Dioïla, Ségou, Pelengaga, Sebougou, Markala, ect., the towns on the outskirts of Bamako e.g Moribabougou, Kalabancoro, Baguineda, Sanakoroba, Tienfala, Banankoroni. The existing network consists mainly of a 150 kV line linking Bamako to the cities of Fana, Ségou in the East, from the Sélingué hydroelectric power station, a 63kV line linking the towns of Ségou and Niono and a 225 kV line (operated by SOGEM) from the Manantali hydropower plant which also connects Bamako with the towns of Kayes and Kita. A second 225 kV line from the city of Ferkessédougou as part of the interconnection with the Ivory Coast, has extended Mali's RI to the towns of Koutiala and Sikasso by connecting them to the 150 kV line Bamako-Fana-Segou in the city of Segou (EMD,2016) (see Figure 2.4).

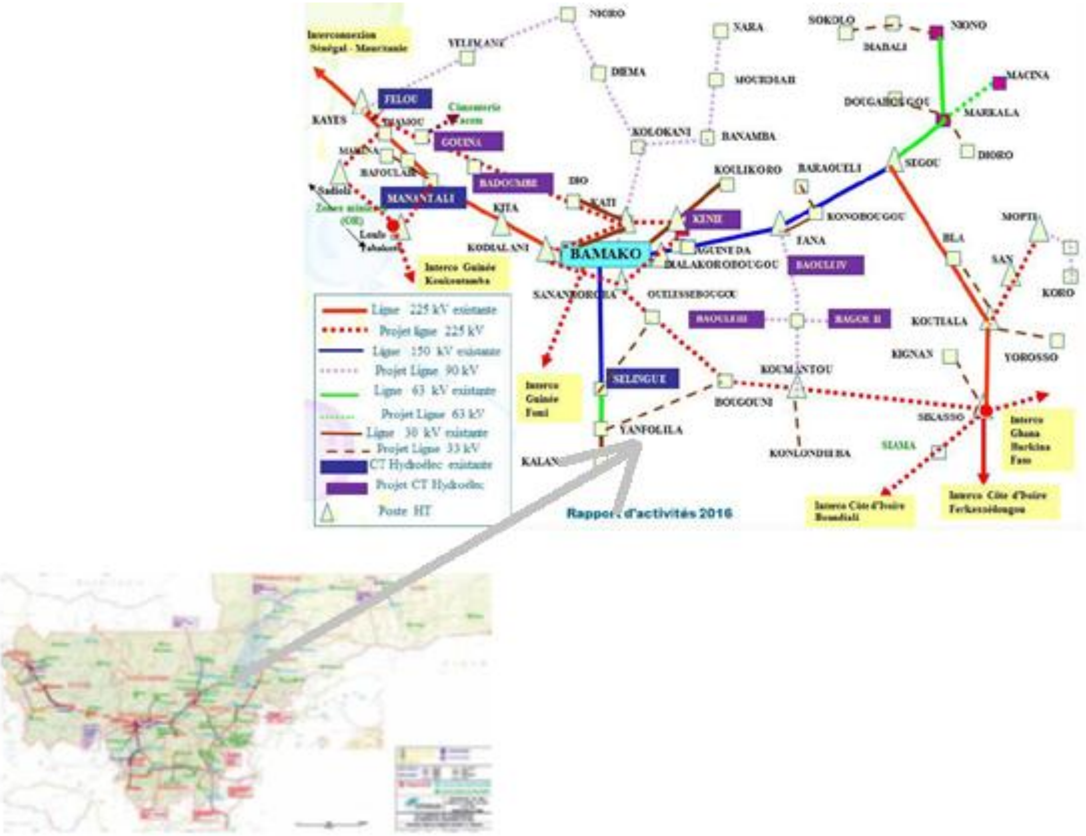

Figure 2.4 : Malian interconnected system

Source: EDM, 2016

2.2.3 Rural electrifications in Mali

Hybrid renewable energy mini-grid power is often known as an off-grid power generation system that is fueled by one or serval renewable energy sources and distributes powers through a local grid network (Yadoo & Cruickshank., 2012). Mini-grids and off-grid systems can be cost-effective solutions for increasing the access of rural populations to electricity and for remote areas and can further reduce the negative impact of unreliable central grid services (REN21, 2015) ensuring more reliable energy supply and energy security for these remote areas. In Mali, small towns outside the existing and planned grid are categorized as included in the rural electrification programme under the responsibility of the Malian agency for the Development of Household Energy and Rural Electrification (AMADER). Access to affordable energy supplies and services can have a tremendously positive impact on rural development and social and economic opportunities for the poor and isolated communities. Rural electrification uses a mix of diesel and PV. About 10% of rural energy services are provided using RE, including mainly small-scale applications such as Solar Home Systems (SHS) (AfDB, 2015).

2.3 Resource assessment

The Malian landscape is two-thirds of territory recovered from dessert. Solar energy resources are shown to be abundant in all of Mali (Togola.,2008). Though the highest values are found in the south, the temporal variation is relatively limited. It also is shown that northern Mali has considerable wind energy potential, while average wind speeds in the southern part are too low to make wind power a competitive option (Nygaard et al., 2010). In Mali the demand exceeds the production from the hydro power plants, and the diesel engines therefore are not only operated as peak load, but generally run as base load. This is a very expensive mean of electricity production, especially with increasing oil prices. Therefore the need for cheaper electricity generation options, thus, the need for sustainable energy production from domestic energy resources. Environmentally friendly renewable energy resources are abundant in Mali and are becoming increasingly competitive such as solar winds; one option for domestic renewable energy resources is agricultural residuals like rice straw and rice hulls from the rice production along the Niger River.(Risø-R-Report., 2012)

2.3.1 Solar Resources

Solar resource is already widely exploited in Mali, the country receives almost 12 h of sunshine with an average daily insolation of 6.3 kWh/m2/day (Diarra & Akuffo., 2017)mainly as solar PV installations, and also as thermal applications used for water-heating, drying and cooking. The current exploitation is mainly the result of long-term efforts of various donors, the private sector and AER (agence pour l’energie renouvellable) . According to information from AER, more than 800 solar pumps providing drinking water and more than 70,000 Solar Home Systems (SHS) had been installed in Mali by 2007. In addition, numerous installations power villages and infrastructure such as dispensaries and schools, while more than 1000 kWp has been installed for telecommunication amplifiers and a non-quantified but smaller number of solar water heaters and solar dryers. Exploitation of solar energy is expected to increase significantly in the years to come due to the reduction of solar energy equipment prices (panel, batteries inverters converter etc.) and also the decline of oil reserves and the increase oil prices. The cost of purchasing solar equipment and installation has significantly decreased since the beginning of the 1980s. Due to increased oil prices, it is predicted that under certain conditions hybrid PV–diesel systems may be more competitive than diesel systems in providing electricity in small isolated grids, as in the case of the many established PV–diesel system in rural areas in Mali (e.g. Kimparana). Likewise, solar PV is expected to fulfill the need to provide electricity to village infrastructure such as water pumps, dispensaries, schools and administrative buildings in non-electrified villages and to provide electricity in terms of SHSs for people living in dispersed settlements and on the outskirts of electrified villages (Nygaard et al., 2010). AMADER uses solar PV-diesel hybrid systems for most rural electrification projects (AMADER, 2015).

2.3.2 Wind Resources

There have been attempts to establish wind power in Mali, but so far wind is only exploited in a few water pumping installation for agricultural and domestic purposes. Mali’s wind energy resource is concentrated in the central and northern parts, from Mopti northwards, where average wind speed of about 3 m/s to 7 m/s is found in large areas, as shown in Figure 2.5. Such wind speeds are generally considered to be the lower limit for the economically feasible exploitation of wind power as a supplement to diesel-driven systems. Since the northern and central parts of Mali are not connected to the national grid, a fair proportion of Mali’s isolated grids are found here. There is hence a scope for supplementing diesel-driven systems with wind parks in the short term. This possibility is currently being explored. A feasibility study for supplying the town of GAO with a wind park of 1 MW, conducted in 2003, showed a reasonable level of feasibility. Another feasibility study for supplying the town of Timbuktu (Tombouctou) from a 1 MW wind park (4 to 275 kW), was finalized in 2009, with a recommendation that wind diesel systems are competitive to pure diesel systems at this size. In the longer term, wind power may contribute to the national grid, as hydro-power resources are unlikely to be able to fulfil the national demand for electricity (Nygaard et al., 2010) .

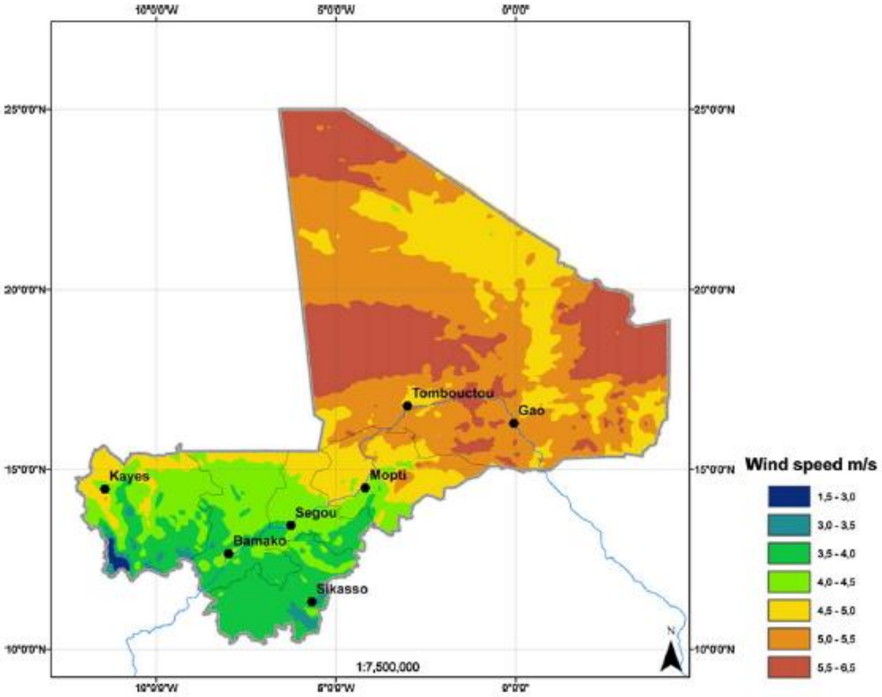

Figure 2.5: Wind Atlas map of Mali

2.4 Biomass (assessment of the potential of rice straw in the office du Niger)

2.4.1 Office du Niger

The Office du Niger is a semi-autonomous government agency in Mali that administers a large irrigation scheme in the Ségou Region of the country. Water from the Niger river is diverted into a system of canals at the Markala dam 35 kilometers (22 mi) downstream of Ségou. The water is used to irrigate nearly 100,000 hectares (390 sq mi) of the flat alluvial plains to the north and northeast of Markala part of the Delta mort. Although the French colonial administration constructed the system to produce cotton for the textile industry, the main agricultural product is now rice. Around 320,000 tons are grown each year representing 40% of the total Malian production. Office du Niger (ON) is used as a case study for the assessment of sustainable resources of rice straw in Mali because it is the most important rice-cultivating area in Mali and the area with the highest concentration of rice straw. In spite of the high pressure on rice straw for cattle feed, agricultural specialists and energy specialists in Bamako suggested in a preliminary mapping that ON was the most interesting place to assess agricultural residues for energy purposes, and to assess the feasibility for large-scale use of straw for electricity production (Nygaard et al., 2016) and is located close to a newly established high voltage transmission line, which will allow for the transport of excess energy from a potential power plant (Nygaard et al, 2012) referring to Figure 2.6.

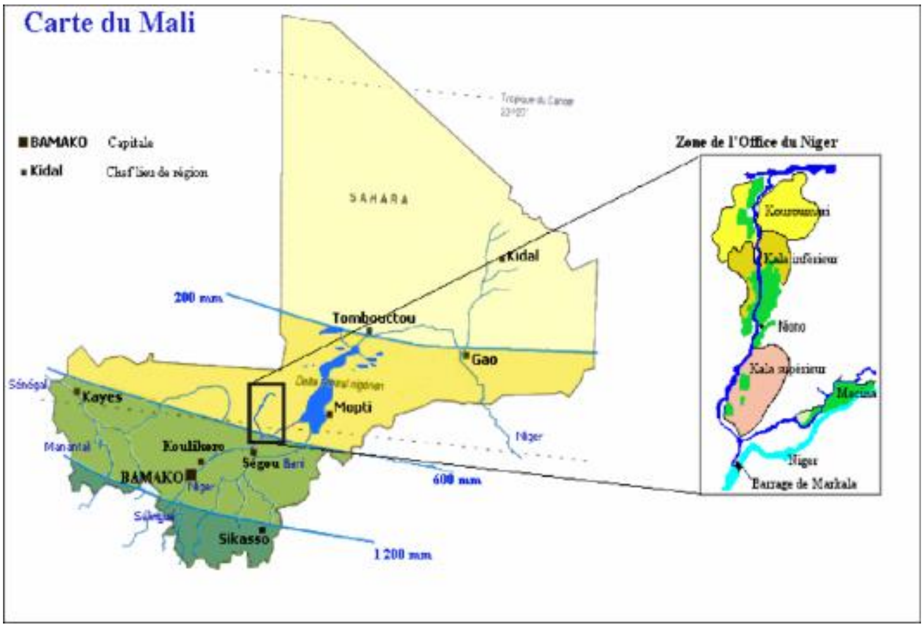

Figure 2.6: Location of office du Niger in Mali

2.4.2 Residue potential in Mali

Biomass from agricultural residues, is considered in developing counties as an increasing biogas and second generation biofuel production and also a sustainable resource for electricity production (Fock., 2012). In this regard, a number of studies of available biomass for energy have been produced at the global level. Available resources include large amounts of leftover material such as stalks, pruning, skins, shells and off-cuts from rice, grain, cotton, vegetables and fruit that are not used as agricultural products. However, residues are a low-density and low-value fuel where transportation costs per unit of energy are high. Additionally, agricultural wastes have limited quantities; they are location specific and are not always of the ideal quality for power generation (Thornley, 2006). The criteria for a crop to be considered 'interesting' from a bio-energy perspective are firstly that there is a significant production of residues, e.g. straw/ husk, concentrated within a limited area (Figure 2.7). Secondly, the alternative uses of this resource, e.g. for fodder purposes, should be of considerably lower, either because the pressure for using it for fodder is low or because the nutritional value of the agricultural residue in question is low. Thirdly, resources that are otherwise burnt like straw, rice husks available at rice mills, often having little value and constitute a disposal problem in many areas are considered particularly interesting, since the potential economic loss associated with using the biomass for energy purposes, may be expected to be low or even negative (Nygaard et al., 2012).

2.4.3 Rice residue in Mali

Office du Niger (ON) is the most important rice cultivating area in Mali, and the area with the highest concentration of rice straw

Table. 2.2: sustainable resources of straw in Office du Niger (tonne/yr)

Zone	Macinca	Bewani	Niono	Molodo	Kouroumari	N'debougou
Harvested rice paddy	105,455	70,1533	85,640	52,081	104,699	85,522
Straw to grain ratio	0.75	0.75	0.75	0.75	0.750	0.75
Share burned	2%	18%	22%	12%	19%	15%
Sustainable resources	1,582	9,471	14,131	4.687	14.134	12,187

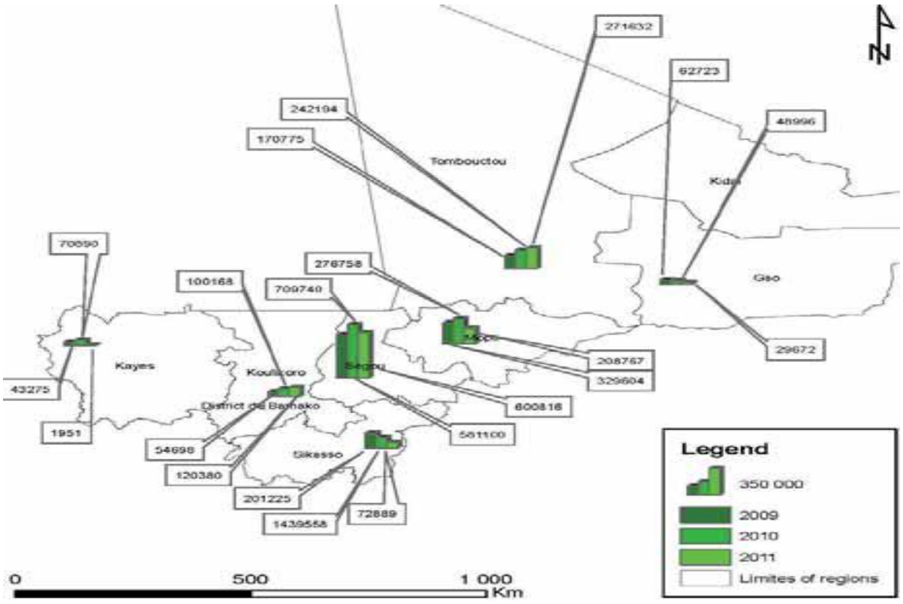

Figure 2.7: Technical potential of rice straw for energy per region in 2009-2011

2.4.4 Use of rice residue

Rice makes up food for more than 3.5 billion people representing half of the world's population, and 91% of it is grown and consumed in Asia. For every 4 tonnes of rice grain, 6 tons of straw are left on the field. In Asia, this amounts to about 550 million tons of straw and 110 million tons of husks each year. The husks are removed from the grains at a mill where they can be used as fuel. By contrast, rice straw remains in the fields after harvest and is costly to gather up in flooded rice systems. Rice straw is bulky and a low-value material hence left on the field. Straw makes up about half of the yield of cereal crops such as barley, oats, rice, rye and wheat. It has many uses, including fuel, livestock bedding and fodder, thatching and basket-making. It is usually gathered and stored in a straw bale, which is a bundle of straw tightly bound with twine or wire. Burning straw in the fields (Figure 2.8) is an old in the office du Niger and in other part of the world to dispose the straw left on the field (practice which has been strongly opposed by the agricultural extension workers from) in order to reduce the risk of bush fires, reduce local air pollution and make use of the fertilizer value of the straw by incorporating it into the soil. Incorporation of rice straw in the soil has been greatly encouraged by the agricultural extension service in the area. Form studies (IRRI, 2018) incorporating rice straw into the soil is not necessary and can be a major cause of methane emissions as its residues break down anaerobically and contributes to global warming through emissions of greenhouse gases (GHGs) (Romasanta et al., 2017). According to farmers, threshed straw is mainly burnt to prevent it piling up on the dikes and fouling up the drainage system. Besides the threshed straw, the stubble is also burned in the fields to combat weeds and to ease cultivation of the next crop. The burned portions of rice can the valorised for electricity production. Biogas can be produced from rice straw by anaerobic digestion. Anaerobic digestion of rice straw is a green technology since it produces better option for waste utilization as well as reducing greenhouse gas emissions by being a substitution for fossil fuels (Murphy and Power, 2009). Furthermore, the potential environmental benefits of diverting rice straw from open-field burning will significantly reduce air pollutants such as VOC, SOx, NOx, and PM10, and also silica emissions, which are not specifically monitored but can be a health hazard.

Figure 2.8 burning rice straw

Source: IRRI, 2018

2.4.5 Nutritional value of rice straw for animal feed

Straws are a poor livestock feed, and rice straw is no exception. It contains about 80%of substances which are potentially digestible and are therefore sources of energy, but the actual digestibility by ruminants is only 45 to 50%. Furthermore, the amount an animal can eat is limited to less than 2% of body weight. Straws contain only 3 to 5% crude protein. Animals fed with un-supplemented straw will actually not gain any weight and very often will lose weight. To obtain any production, the straw must be supplemented, preferably with nitrogen/ protein and energy. For good growth on straw diets, a level of 8 to 10 percent protein is needed for young stock; this also improves consumption and thus increases energy intake. The level of phosphorus in rice straw (0.02 to 0.16 %) is less than the level of about 0.3 percent that animals need for growth and normal fertility. A level of about 0.4 % of calcium in the diet is usually considered adequate for livestock, and many samples of rice straw have this amount, the range being from 0.25 to 0.55%. Nevertheless, many balance experiments with cattle fed rice straw have shown negative balances of calcium even when the calcium content of the straw was apparently adequate (Nath et al., 1969). While the significance of these negative calcium balances has been questioned, the fact remains that in the same experiment higher positive calcium balances have been observed on wheat straw and sorghum stover diets than on rice straw diets, even though the calcium intake on the rice straw diets was higher. It would therefore seem prudent to feed calcium supplement with rice straw diets.

2.4.6 Nutritional value of rice straw for soil fertilization

Some growers incorporate the straw into the soil by chopping and plowing in Incorporation of the straw is more forbidding than burning because the long straw tends to clog field implements, and is also costlier than burning. The straw is resistant to decay and can interfere with succeeding years' operations if not plowed under to greater depths than standard operations call for. Soil-incorporating straw may reduce yields particularly in cool climates and in poorly drained fields. A potential hazard of utilizing rice straw off-field is nutrient depletion. Soil analysis appears to indicate that soil nutrients are being depleted and will require the addition of certain nutrients to compensate for this loss. Spring harvesting avoids potassium loss, but leads to organic matter losses during over wintering(Kadam et al., 2000).

2.4.7 Environmental Impact of Incorporating and Open Field Burning Rice Straw

Rice is a widely grown crop that leaves a substantial quantity of plant residues in the field such as roots, stubbles, and straw after harvesting. As discussed in straw usage: scattered in the field to be incorporated to the soil fertilize, mushroom production, fuel for cooking, ruminant fodder, stable bedding and paper making in several developing countries developed countries (Liu, Z et al 2011). Straw makes up about 50% of the dry weight of rice plants, with a significant variation from 40 to 60% according to the cultivar and cultivation method. For every tonne of grain harvested, about 1.35 tonnes of rice straw remain in the field. Rice straw has a high potential as a source of lignocellulose biomass because of the high yield of rice straw per hectare. The proportion of recoverable (recoverability factor) straw depends on the technique of reaping and harvesting. Rice straw was usually disposed of by open-field burning because it is a cheap disposal method.(Kadam et al., 2000). The straw is often burnt in the field in most developing country especially in Asia and in the Philippines 95% of the straw undergoes this process (Gadde et al., 2009). Several attributes could influence straw burning and its emissions. Water content or moisture in plants can either prevent a fire completely or slow down the burning process and eventually terminate the fire. Density and structure of biomass are other characteristics to be considered for combustion properties. Rice straw burned in the field increases the emission of greenhouse gases (GHGs), such as methane (CH_4), at a rate of 1.2–2.2 g per kg dry straw it pollutes the air and contributes to global warming through emissions of greenhouse gases (GHGs). (Romasanta et al., 2017), greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide

(N2O). These gases affect human health through emission of air pollutant and could cause loss of soil nutrients, almost complete N loss, 25%, of p, 20% of K and about 5-60 % of S losses. (Dobermann and Fairhurst., 2002). Rice straw burning has advantages in terms of farm operations but disadvantages from an environmental perspective. Burning allows for rapid and complete residue removal, but it could result in the loss of major nutrients (Romasanta et al., 2017; Dobermann and Fairhurst, 2002). Additionally, biomass burning is the second-largest source of trace gases and the largest source of primary fine carbonaceous particles in the global troposphere. Intensive burning of agricultural wastes may substantially contribute to the formation of Atmospheric Brown Cloud (ABC) that affects local air quality, atmospheric visibility, and Earth's climate. In case the rice straw is fed to cattle, the overall GWP will be high. Rice straw has low nutritional value and entails high methane emission rates, rice straw use as animal feed result in a net increase of 13% in total GWP compared to straw burning. Other applications of straw, for example, mushroom production, power generation or bio ethanol production entail lower total GWP found that straw-mushroom cultivation had 12.5 percent lower total GWP than straw burning. It was estimated that 0.378 tonnes CO_2eq/t straw and 0.683 t CO_2eq/t straw could be avoided if rice straw substitutes natural gas or coal in the power generation sector (Romasanta et al., 2017).

2.5 Biomass Assessment/ biomass potential for electricity generation

Mali already produces a lot of biodiesel from the jatropha to operate multifunctional platforms in remote rural villages. However being agricultural zone specially in the Ségou, Sikasso region in the cross region with office du Niger where a lot of agricultural post harvesting residues are burnt in the field which could represent a lot of biomass resource and contribute of a large percentage in the country energy balance. These resources represent cassava, maize, yam, cocoyam, cocoa, plantain rice, sorghum, sugar cane, millet etc., all those resources which are not and burnt in the field are important resource in biofuel (bioethanol, biodiesel) production (Nygaard et al., 2012). Biomass assessments are calculated by using a certain potential. Most typically used are theoretical, technical, economic, and sustainable potentials. (Vesterinen.,2010). To assess potentials of biomass for energy some parameter are often defined: theoretical potential, technical potential, economic potential and implementation potential. Sometimes a geographical potential, ecological potential and sustainable potential are added (No, 2010). These potentials are not always defined in the same way, and some of them overlap. One recent study groups the definitions into three main categories: theoretical, technical, and market (economic) potential. Within the three categories the author defines the ecological potential as a subset or limited part of the technical potential, and the implementation potential as a subset of the economic potential (Nygaard et al., 2016).A comprehensive and detailed assessment of the available bioenergy potential is therefore essential to determining the contribution which biomass and biofuels can realistically make to the world's energy system. (Deng et al.,2015)

2.5.1 Theoretical potential

Theoretical potential is considered to be the maximum amount of terrestrial biomass that is theoretically available for bioenergy production within fundamental biophysical limits. This represents the maximum productivity under theoretically optimal management of agriculture and forestry, taking into account limitations that result from temperature; solar radiation and rainfall. For agricultural residues, the theoretical biomass potentials represents the total residue production.(Batidzirai, Smeets, & Faaij, 2012)

2.5.2 Technical potential

The technical potential is defined as the fraction of the theoretical potential which is available under current technological possibilities, and taking into account spatial restrictions due to competition with other land uses (food, feed and fibre production) as well as other non-technical constraints. When restrictions related to environmental criteria such as nature conservation and soil/water/biodiversity preservation are considered then this fraction of technical potential is referred to as the ecologically sustainable potential. (Batidzirai et al., 2012) The technical potential of rice straw for energy production is estimated based on the uniform straw-to-grain ratio. Technical potential of rice straw is calculated by multiplying a straw-to-grain ratio (residue-to-product ratio) to the statistical information of annual production of paddy rice, which depends on the soil quality, the fertilizer level the cutting height when harvesting the rice and the rice variety (type). In Mali there are quite a number of rice varieties. The cutting height is relative to the wish of the farmers to reduce the amount of rice straw to be left on the field. The GAMBIAKA variety is the most grown in the regions of Office du Niger with a rate of 68 % verities like ADINY, WASSA, GB, SAMBALA MALO etc. In the selected study site this seems de be the same practice. Straw to gain ratio results for the some of the rice grown in Mali are present in the table (Nygaard et al., 2012).

Table 2.3: straw-to-gain ratio

Variety	Share of production %	Straw to gain ratio
Gambiaka	68	0.58
Adiny 11	12	0.75
Wass	12	0.75
BG	3	0.75
Sambala malo	2	0.75
Ier 32000	1	0.75
Nerica	0	0.75
Average	100 %	0.63

2.5.3 Environmental Potential

The economic potential is the share of the technical potential which meets criteria of economic profitability within the given framework conditions. The economic potential generally refers to secondary bioenergy carriers, although sometimes also primary bioenergy is considered.

2.5.4 Implementation Potential

The implementation potential is the fraction of the economic potential that can be implemented within a certain time frame and under concrete socio-political framework conditions, including economic, institutional and social constraints and policy incentives. Studies that focus on the feasibility or the economic, environmental or social impacts of bioenergy policies are also included in this type. The classification in types of biomass potentials helps the reader to understand what information is presented. For instance, some biomass types show high technical potentials while their economic potential is rather limited due to the high costs of extraction and transport. Therefore it is recommended that the type of potential is explicitly mentioned in every biomass resource assessment. In existing resource assessments, it is often difficult to distinguish between theoretical and technical potential and between economic and implementation potential. The technical and theoretical potential and the economic and implementation potential form two pairs of potential types. However, even more important than making this distinction between four types is the provision of insight into explicit conditions and assumptions made in the assessment.

2.5.5 Sustainable implementation potential

The sustainability criteria act like a filter on the theoretical, technical, and economic and implementation potentials leading in the end to a sustainable implementation potential. It is not a potential on its own but rather the result of integrating environmental, economic and social sustainability criteria in biomass resource assessments. Depending on the type of potential, sustainability criteria can be applied to different extents. For example, for deriving the technical potential, mainly environmental constraints and criteria are integrated that either limit the area available and/or the yield that can be achieved. Applying economic constraints and criteria leads to the economic potential and for the sustainable implementation potential, additional environmental, economic and social criteria may be integrated (see Figure 2.9). The fraction of the technical potential which can be extracted in an economically viable manner without causing social or ecological damage. In the Malian context, particularly in the study are case this is interpreted as the fraction which is currently being burned and again the industrialization and studies a certain percentage of the portion that was incorporated into the soil or use as animal feed (non-efficiency of the practice like state up the generation of more GHG the low nutritive value of the straw and the alteration of the soil productivity or yield).

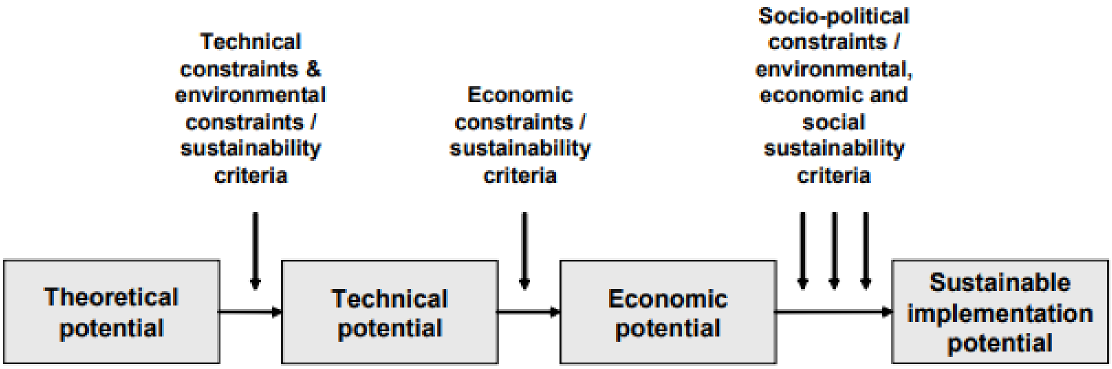

Figure 2.9: biomass potential assessments

2.5.6 Agricultural residues Available for Electricity for Production in Office Du Niger

Among the food grains, rice is the main cereal produced in the state in terms of production and cropped area (see Figure 2.9) (Nygaard et al., 2012). The cultivation of rice results in two major types of residues. Straw and Husk having attractive potential in terms of energy. Although the technology for rice husk utilization is well-proven in industrialized countries of Europe and North America, such technologies are yet to be introduced in the developing world on commercial scale. The importance of Rice Husk and Rice Straw as an attractive source of energy can be gauged from the following statistics (referring to figure 2.10 rice production profiles for detail).

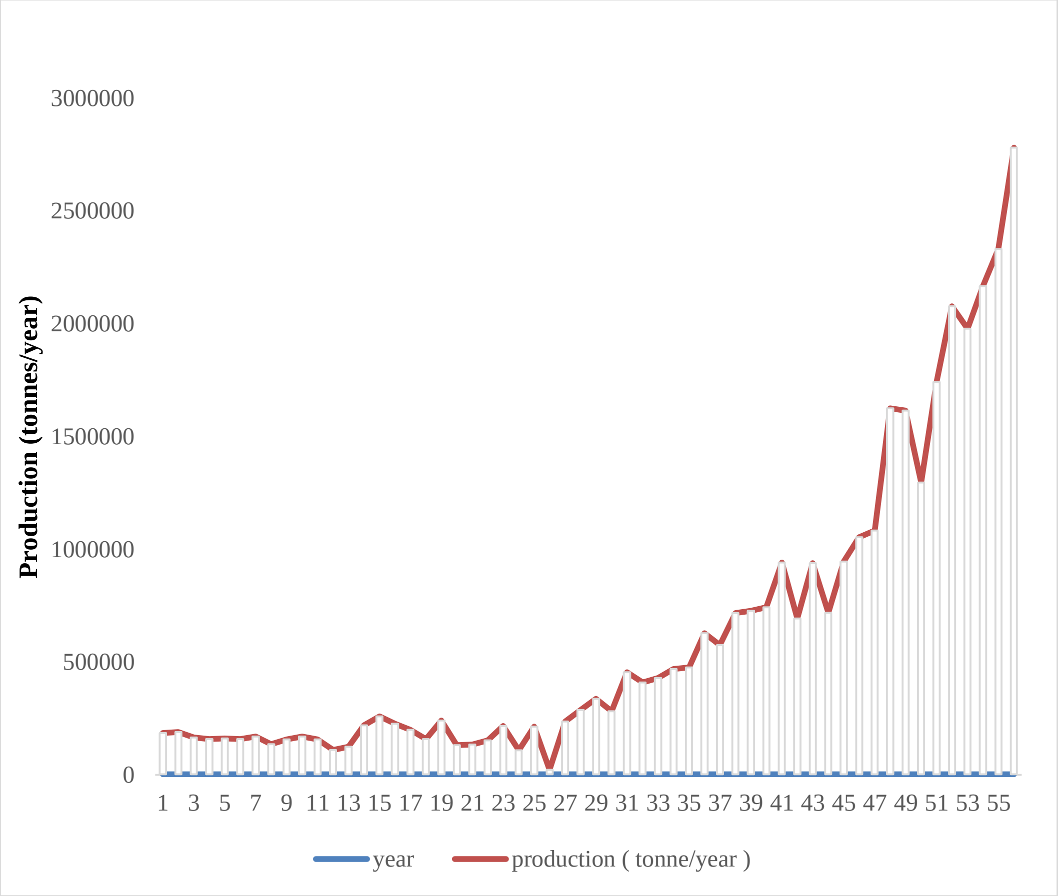

Figure 2.10: Rice production profile form year 1961-2016

2.6 Lignocellulose Biomass processing Technologies overview

Biomass can be used to produce transportation fuels, or chemicals, useful energy (heat or electricity) or energy carriers (charcoal, oil or gas) by: Thermochemical conversion technologies including combustion, gasification and pyrolysis; Biochemical conversion technologies which include fermentation for alcohol production and Anaerobic digestion for production of methane (see Figure 2.11 for details). The use of biomass for any of these purposes is called biomass energy. Direct combustion is still the most conventional way to produce energy from biomass.

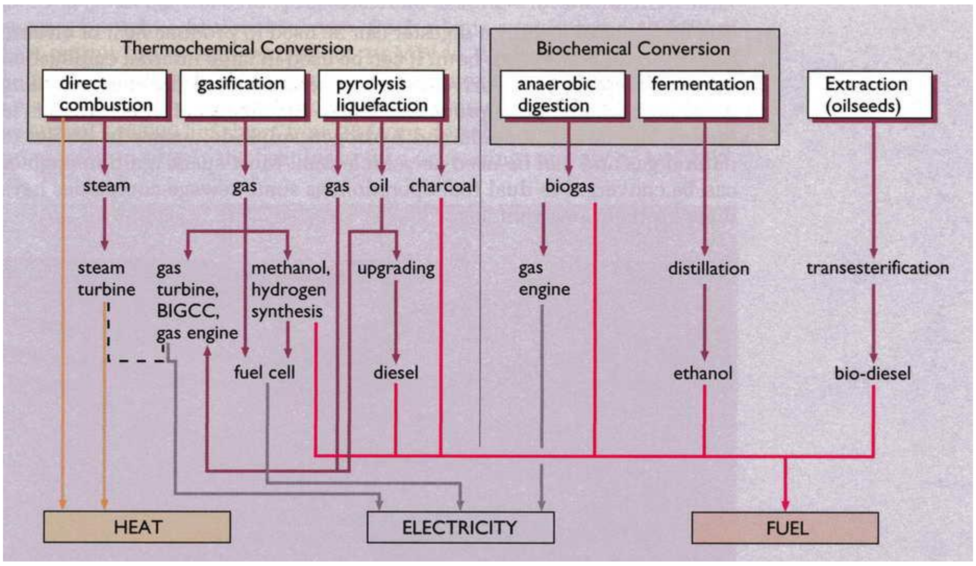

Figure 2.11: Pathway from biomass the electricity

Each category of the technologies has undergone significant development, and therefore, different methods are available. Pyrolysis is the thermal destruction of biomass in an anaerobic environment, without the addition of steam or air, to produce gases and condensable vapours. Combustion of these gases occurs in a gas turbine, typically a combined-cycle gas turbine. In gasification, biomass is partly oxidised by controlling oxygen with the addition of steam to produce combustible gases that have a high calorific value. Product gases are fed into a combined-cycle gas turbine power plant. Direct combustion is the complete oxidation of biomass in excess air to produce carbon dioxide and water. Hot flue gases are used to heat-process water to steam, which drives a turbine, typically via a Rankine cycle. Direct combustion is the oldest and simplest, but most inefficient, technology. Gasification and pyrolysis have higher efficiencies but require significantly more process control and investment (Strezov & Evans., 2015).

2.6.1 Gasification

Gasification is a means of converting a diversity of solid fuels to combustible gas or syngas (Faaij., 2006). Biomass gasification is one of the most promising technologies because of its ability to rapidly convert large amounts and various kinds of biomass into easily storable and transportable gas or liquid fuel. It is the incomplete combustion of biomass resulting in production of fuel gas consisting of Carbon monoxide (CO), Hydrogen (H_2) and traces of Methane (CH_4). Biomass gasification is usually performed at high temperatures (>800°C) and the composition of the product depends on the gasifier’s design and operational conditions. The heating value of synthesis gas (or syngas) is usually about approximately 4 to 6 MJ/m^3 when using air as the gasifying agent, whereas it can reach as high as 12 to 20 MJ/m^3 using pure O_2. The raw material for gasification include agriculture residues such as rick husks, corn straws, rice straws, wheat straws, cotton straws, fruit shells, coconut shells, palm shells, bagasse, corncobs, energy crops, forest wood residues including wood powder, branches, offcuts, etc. (Power Machinery Co. Ltd.,2018). Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel (Calvo et al., 2012). Biomass gasification is the most reliable and promising method nowadays to generate electricity, because this process provides sustainable & affordable alternative to fossil fuel based process plants at small and medium levels (Ġbrahim et al., 2016). Rice straw is problematic for burning in most existing combustion systems because of its high alkali content, which causes boiler operational problems, such as slagging and fouling. Gasification may ameliorate these problems, providing fuel flexibility and high thermal efficiency since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air is introduced in it. There are three types of gasifiers; Downdraft, Updraft and Cross-draft (Figure 2.12). As the classification implies, updraft gasifier has air passing through the biomass from bottom and the combustible gases come out from the top of the gasifier. Similarly, in the downdraft gasifier the air is passed from the tuyere in the downdraft direction. Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are: Drying of fuel, Pyrolysis, Combustion and Reduction (Rajvanshi., 2014). Gasification plant typically consists of the following units:

- Gasifier
- Syngas cleaning units (engine/turbine requirements)
- Gas engine/turbine with generator (power generation plant
- Heat recovery/steam generation
- Steam engine/turbine with generator (combined cycle plant).

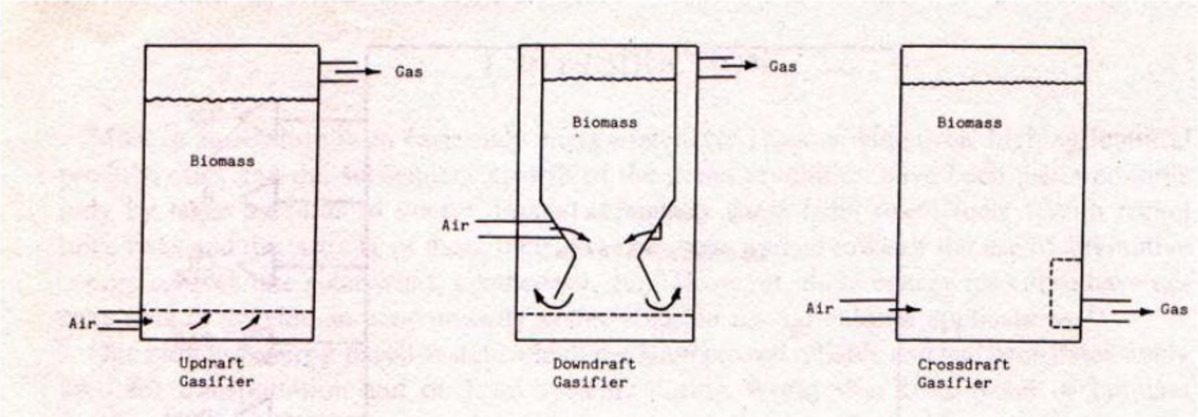

Figure 2.12: Type of gasifiers

Source: (Rajvanshi, 2014)

2.6.2 Anaerobic digestion

Anaerobic digestion is the conversion of biodegradable organic materials (Agricultural waste, Food waste, Municipal waste) through the process of fermentation in absence of air to yield useful by-products. The products of anaerobic digestion are biogas (typical a gas of 60percent methane and 40percent carbon dioxide) (Shitophyta & Fuadi., 2016) and nutrient-rich digestate, which is typically employed in agriculture as fertilizer. Biogas burns directly in a gas boiler to produce heat or in a combined heat and power (CHP) unit to produce heat and electricity. It provides solutions to waste management, enables better odour management and hygiene, prevent pollution with less greenhouse gas emitted. Energy recovery can be a sustainable option for waste that would otherwise go to landfill and create landfill methane emissions. The production of biogas is one of the most efficient and environmentally beneficial methods of extracting energy from biomass. Approximately 90% of the energy from degraded biomass is retained as methane (IEA, 2005). Anaerobic digestion is more cost-effective over the course of its life cycle compared with other waste treatment options. Biogas generation through anaerobic digestion process consists of four stages: Hydrolysis; the first stage sees the breakdown of complex matter, such as carbohydrates and proteins, broken down into sugars and amino acids. These are normally long chain chemical compounds, but Hydrolysis breaks them down into single molecules. Acidogenesis is the second stage, where microorganisms break down the single molecules of sugar and amino acids even further into ethanol and fatty acids, as well as producing carbon dioxide and hydrogen sulphide as by-products. Acidogenesis is the third stage, where the ethanol and fatty acids are converted into hydrogen, carbon dioxide and acetic acid. Methanogenesis is the fourth and final stage; microorganisms convert the remaining hydrogen and acetic acid into methane and more carbon dioxide. (opusenergyblog., 2018). Table 2.4 presents the feedstock type and the biogas yield per dry matter estimated. (Kwaku et al., 2017). Biogas production through Anaerobic digestion is affected by some parameters such as Temperature, Hydraulic retention time (HRT), Solid retention time (SRT), Air or oxygen content, Carbon-Nitrogen (C/N) ratio, pH (acidic, neutral or alkaline) etc. Temperature is not only important for microbial metabolic activities but also for the overall digestion rate, specifically the rates of hydrolysis and methane formation. In general, anaerobic digestion process can occur within a wide range of temperatures. Most of the digesters are designed to operate at , between 30 to 38 ^{o} C for Mesophilic plants, and 50 to 57 ^{o} C for thermophilic plants (Shyue Koong Chang & Schonfeld, 1991) (Metcalf and Eddy, 2003).

Table 2.4: Typical composition of biogas

compound	formula	%
Methane	CH_4	50-75
Carbone dioxide	$C0_2$	25-50
Nitrogen	N_2	0-10
Hydrogen	H_2	0-1
Hydrogen Sulfate	H_2S	0-3
Oxygen	O_2	0-0

Source: (kolumbus, 2007.)

2.6.3 Direct combustion

Among the thermochemical conversion technologies, combustion is the most direct process for converting biomass into usable energy (Figure 2.13). Combustion can be broadly defined as the burning of any biogenic substance. Nature of combustion depends on fuel properties and combustion application. Combustion process can be divided into several general processes as follows:

- Drying, this involves evaporation of the contained water.
- De-volatilisation, the thermal decomposition of the fuel into volatile gases and solid char.
- Combustion of the volatiles in which the volatile gases burn, showing yellow flames.
- Combustion of the char: the solid char is combusted, and its burning is characterized by small blue flames or glowing of the char pieces.

The efficiency of combustion and the ability to exploit the energy within depends on the type of biomass, combustion method; scale and application. The three main combustion techniques for biomass in heat and power applications are the same as for coal, namely, grate firing (GF), fluidized bed (FB) and pulverized fuel (PF). Grate-firing: biomass is placed on a grate and material is moved slowly through the boiler as it combusts with air being supplied through holes in the grate. Particularly suited for coarse and uneven particle sizes but maximum size is limited to approximately 150 MWth/50 MWe. Fluidized bed (FB): biomass is mixed with a medium (typically sand) and kept suspended in a mix with incoming air. The temperature in the 'bed' allows a part gasification of the biomass and the method can therefore be used with relatively coarse and wet material (compared to PF). The lower temperature also reduces the 0Nox and Sox emissions associated with the combustion. The size generally varies from 30–300MWe. Pulverized fuel: biomass is grinded to powder and combusted. PF achieves high efficiency in combustion and can be applied in large scale (up to 600MWe), but during grinding, the feedstock requires energy (Wolf, 2013). It uses dry feedstock. Cogeneration or Combined Heat and Power (CHP), is the process of using a heat engine or power station to simultaneously produce both power and usable thermal energy from a single fuel source (Figure 2.14).

Combustion plant typically consists of the following units:

- Furnace/boiler
- Heat recovery/steam generation
- Steam engine/turbine with generator (power generation plant)

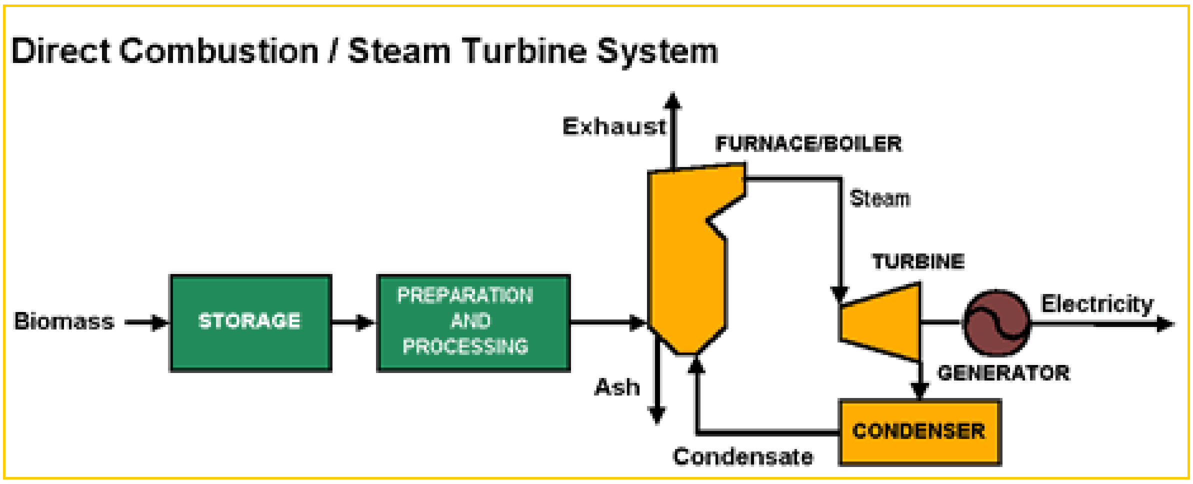

Figure 2.13: biomass generation plan

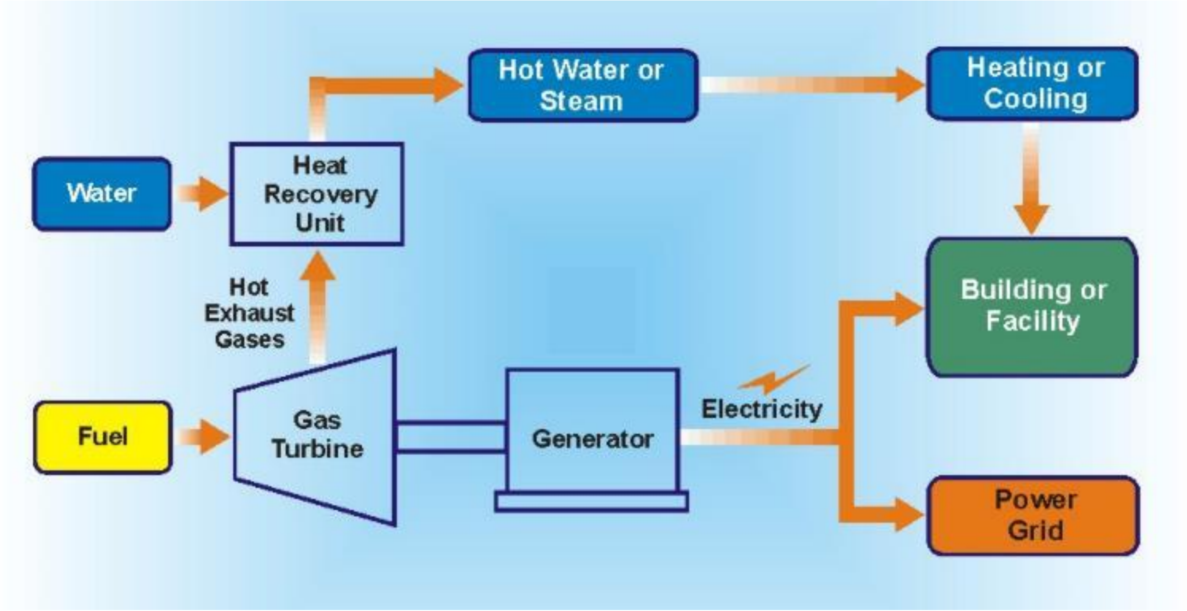

Figure 2.14: biomass generation plan with heat recovery system for building heating

2.7 Hybrid Renewable

2.7.1 Integration configurations

All renewable energy sources have their own different operating characteristics, it is necessary to make a standard procedure for integrating renewable energy sources in integrated system. Generally, there are three possible configurations to integrate different renewable energy sources : DC coupled configuration, AC coupled configuration, Hybrid coupled configuration.

2.7.1.1 DC coupled configuration

The configuration has only one DC bus and all renewable energy sources are connected to the bus by proper power electronics interfacing circuits. DC producing power is directly connected to DC bus. DC loads are served from DC bus through DC/DC converters to maintain constant DC voltage level at the user end. This configuration can also supply power to AC loads through an inverter. This configuration is simple as synchronization is not required to integrate various energy sources. When the inverter fails then whole system will unable to supply energy to AC load. This problem might be eliminated by using several small rating synchronized inverters, connected in parallel to supply AC power. A DC coupled configuration of small hydro–wind–solar based integrated system is given in Figure 2.15(Chauhan & Saini, 2014).

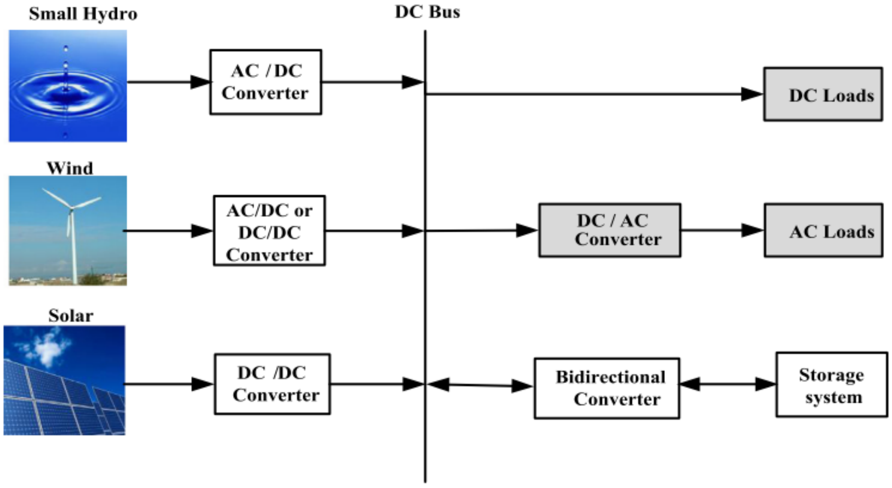

Figure 2.15: DC coupled configuration of small hydro–wind–solar based integrated system

Source: (Chauhan & Saini, 2014)

2.7.1.2 AC coupled configuration

This integration configuration can be categorized into two configurations as power frequency AC coupled (PFAC) and high frequency AC (HFAC) coupled. Different energy sources are connected to power frequency AC bus through appropriate power electronics circuits. Storage system is connected to bus through bidirectional converter. AC loads are directly connected to bus and DC loads are connected to PFAC bus through AC/DC converter. Synchronization among various system components is not required in PFAC based coupled system. In high frequency AC (HFAC) coupled configuration, different sources are coupled to HFAC bus. This configuration is extensively used in high frequency loads like airplanes, sub-marines and space station applications. Schematic of PFAC coupled configuration of wind–solar based integrated system is shown in Figure 2.16 (Chauhan & Saini, 2014).

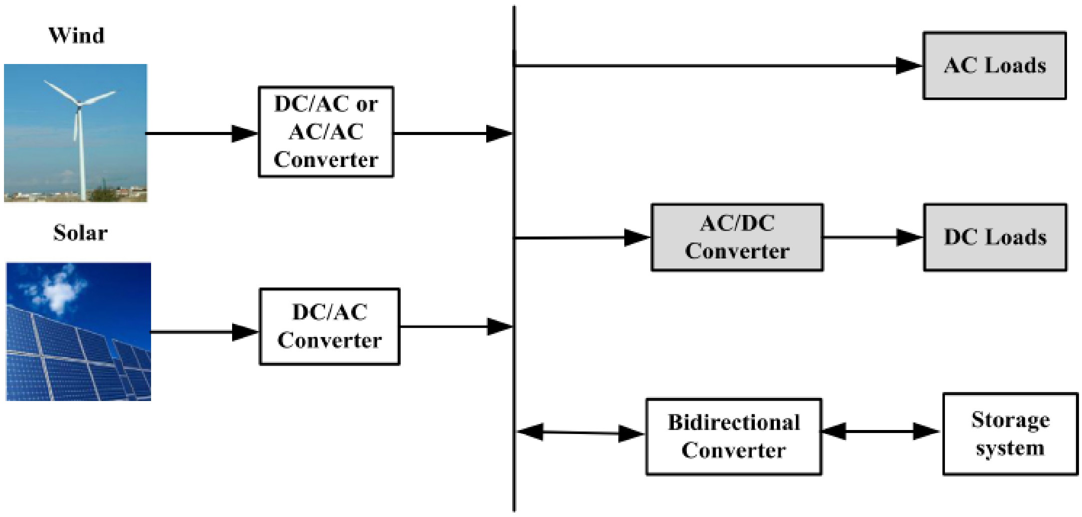

Figure 2.16: AC coupled configuration of wind–solar based integrated system

Source: (Chauhan & Saini, 2014)

2.7.1.3 Hybrid DC–AC coupled configuration

Hybrid scheme has both DC and PFAC bus. In this scheme, all DC energy sources (solar) are coupled to DC bus by proper interfacing circuits. DC loads are directly served through DC bus by using DC/DC converter (if required). AC loads receives energy from PFAC bus (50–60 Hz). In this control scheme, PFAC energy sources can be directly connected without any interfacing circuits. This eliminates the use of converters and hence reduces conversion losses in the configuration. As a result, hybrid DC–AC coupled configuration has lower cost and higher energy efficiency as compared to DC coupled and AC coupled schemes. But hybrid scheme has relatively complex control and energy management. Hybrid coupled configuration of small hydro–wind–solar based integrated energy system is presented in Figure 2.17. system (Chauhan & Saini, 2014).

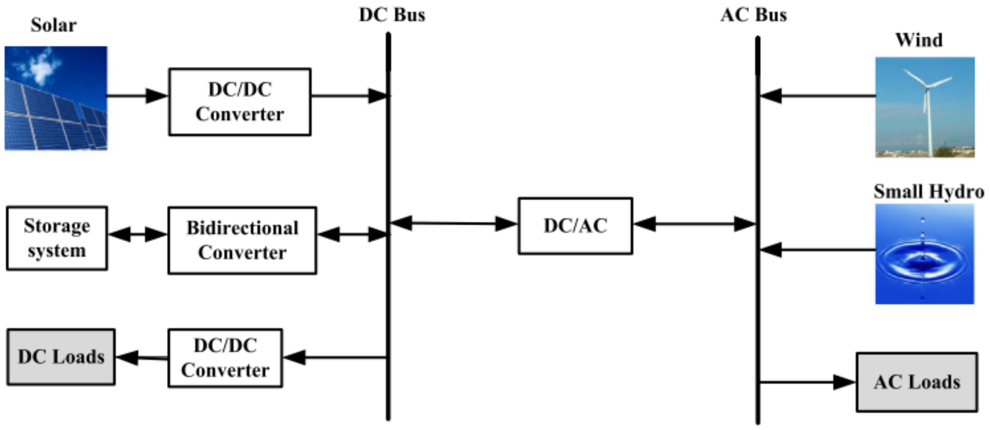

Figure 2.17: Hybrid coupled configuration of small hydro–wind–solar based integrated energy system

Source: (Chauhan & Saini, 2014)

Table 2.5: IRES configuration

Configurations	Merit	Demerit
DC coupled	Simple and no synchronization is needed to integrate the different renewable	In the absence of inverter, this configuration is not able to supply power to AC load.
AC coupled	Suitable configuration for domestic, industrial applications in present scenario as most of the AC appliances may directly connected to AC bus.	Need to synchronize the incoming generator output with AC bus and also required a converter to supply DC load.
Hybrid DC–AC coupled	Higher efficiency and lower system cost. Conversion losses are very low as AC and DC loads might be directly connected to their respective buses.	The Control and energy management is complex than DC and AC coupled schemes

Source: (Chauhan & Saini, 2014)

2.7.1.4 Hybrid Renewable Energy Systems

In rural communities, electricity access is a challenge, and grid extension can be expensive. A hybrid renewable energy system can either be stand-alone or grid-connected if a utility grid is available. For a stand-alone application, the system needs to have sufficient storage capacity to handle the power variations from the renewable energy sources involved (Balamurugan et al., 2009). Some remote areas have not sufficient renewable resources; therefore IRES are often some conventional fuel diesel/petrol/gasoline is incorporated to IRES system to compensate the intermittent character of these resources to meet energy needs. It reduces the dependence on the conventional sources importation cost for countries that don't have national fossil-fuel reserve. The main advantage of such systems is that weakness from one source is covered by others (Akikur., 2013). Single technology based system (solar photovoltaic / wind / small hydro) is a viable option to supply energy to these remote areas. Small remote villages that are far away from the utility grid can be electrified by single technology. Single technology system cannot provide a continuous source of energy due to the low availability during different seasons. In order to achieve the high energy availability, it is necessary to oversize the rating of the generating system (e.g., surface of the photovoltaic array, rating of wind turbine). Single technology based system are associated with high system cost and low reliability due to high energy requirements. Single technology systems are well suited for small locality having limited energy need (Chauhan & Saini, 2015). Integrated Hybrid renewable energy systems (IRES) have great potential to provide higher quality and more reliable power to customers than a system based on a single resource (Balamurugan., 2009). Integrated Renewable Energy System (IRES) has been highly promoted by researchers to electrify remote areas. In IRES, energy demand of a remote area is met by using energy potential of locally available renewable energy sources. In this technology, renewable energy sources like solar, wind, Micro Hydro Power (MHP), biomass, biogas etc. can be considered for Power generation. Integrated use of different renewable energy resources minimizes energy storage requirement, increases reliability of power supply and quality of power. Control system is the heart of IRES that provides the information and communication among various components of system and regulates power output and also, generates the signals for scheduling of storage subsystem and dump load, protects the storage system from overcharging and helps to operate the storage system in prescribed limit.

Whenever surplus energy is available, it is sent to storage subsystem to store the surplus energy and if storage system if fully charged. (Chauhan & Saini.,2014).The advantages of using locally controlled micro-grids are the reduction in the overall energy consumption and the environmental impact, improvement of the energy efficiency, reliability of the energy supply, transmission losses reductions, voltage control, and security of the energy supply. The micro-grid energy system can be connected to the utility grid (synchronized with traditional centralized grid) or can operate separately off grid (disconnected from the grid and function autonomously) (Ghenai & Janajreh., 2016). (Nazir et al. 2014) investigated a simple micro-grid model integrates the power plants driven by renewable energy sources employing micro-hydro and photovoltaic system which is connected to grid system with optimization of the local renewable energy for on-grid area. The results show the performances of the power plants and the maximum power produced from renewable energy sources. The micro-grid model with the largest capacity MHP produced the lowest energy cost, greatest reduction of CO_2 emission, and largest fraction of renewable energy. However, this system required high initial capital cost (Ghenai & Janajreh., 2016).

2.7.2 Renewable Hybrid Mini-Grid Systems with Biomass (HRES)

Rural areas produce enough biomass and agricultural residues so that their electricity demands can be met by using biomass gasifier-based power plants. Apart from providing the rural communities energy self-sufficiency, these plants can also generate enough employment opportunity for the rural people. Rural employment and wasteland development is possible through this sustainable and renewable source of energy (Balamurugan et al., 2009). However, while it is true that many off-grid renewable energy technologies may be more expensive and dependent on favorable weather conditions than a liquid fuel source such as diesel, these criticisms do not project the full story. Firstly, as shown in Figure 2.18, on a levelised cost basis (that is, when capital and operating costs are totaled over the plant’s economic lifetime using a 10% discount rate), several renewable energy technologies (such as biogas digesters, biomass gasifiers and micro-hydro plants) are already cheaper than diesel generators, particularly in light of their ‘‘high capacity factors and availability of size ranges matched to mini-grid loads (Yadoo & Cruickshank, 2012 ; ESMAP, 2007)

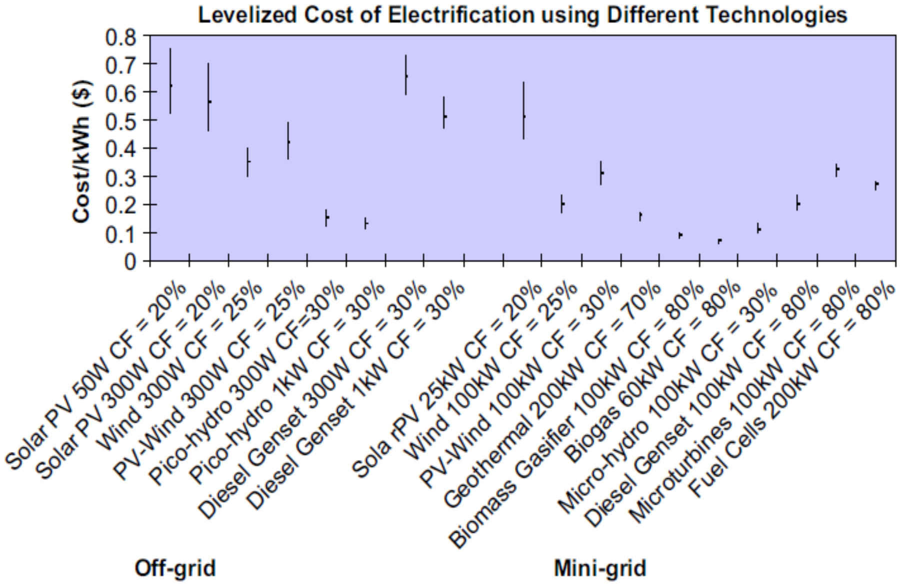

Figure 2.18: Levelised cost of electrification using different technologies

Source: (ESMAP, 2007) CF : Capacity factor.

2.7.3 HOMER software

HOMER (Hybrid Optimization of Multiple Electric Renewables), simplifies the task of evaluating designs of both off-grid and grid-connected power systems for several of applications. The software requires initial information including energy resources, economic and technical constraints, energy storage requirements and system control strategies. Inputs like component type, capital, replacement, operation and maintenance costs, efficiency, operational life, etc. are also required (Chauhan & Saini., 2014). HOMER uses these inputs to simulate different system configurations, or combinations of components, it compares various design configurations on the basis of their technical and economic merit and generates results that can view as a list of feasible configurations sorted by net present cost (HOMER, 2016). HOMER includes several energy component models, such as photovoltaics (PVs), wind turbines, hydro, batteries, diesel and other fuel generators, electrolysis units, and fuel cells, and evaluates suitable options considering cost and availability of energy resources The architecture of the software is presented in Figure 2.19 (Erdinc & Uzunoglu., 2012).

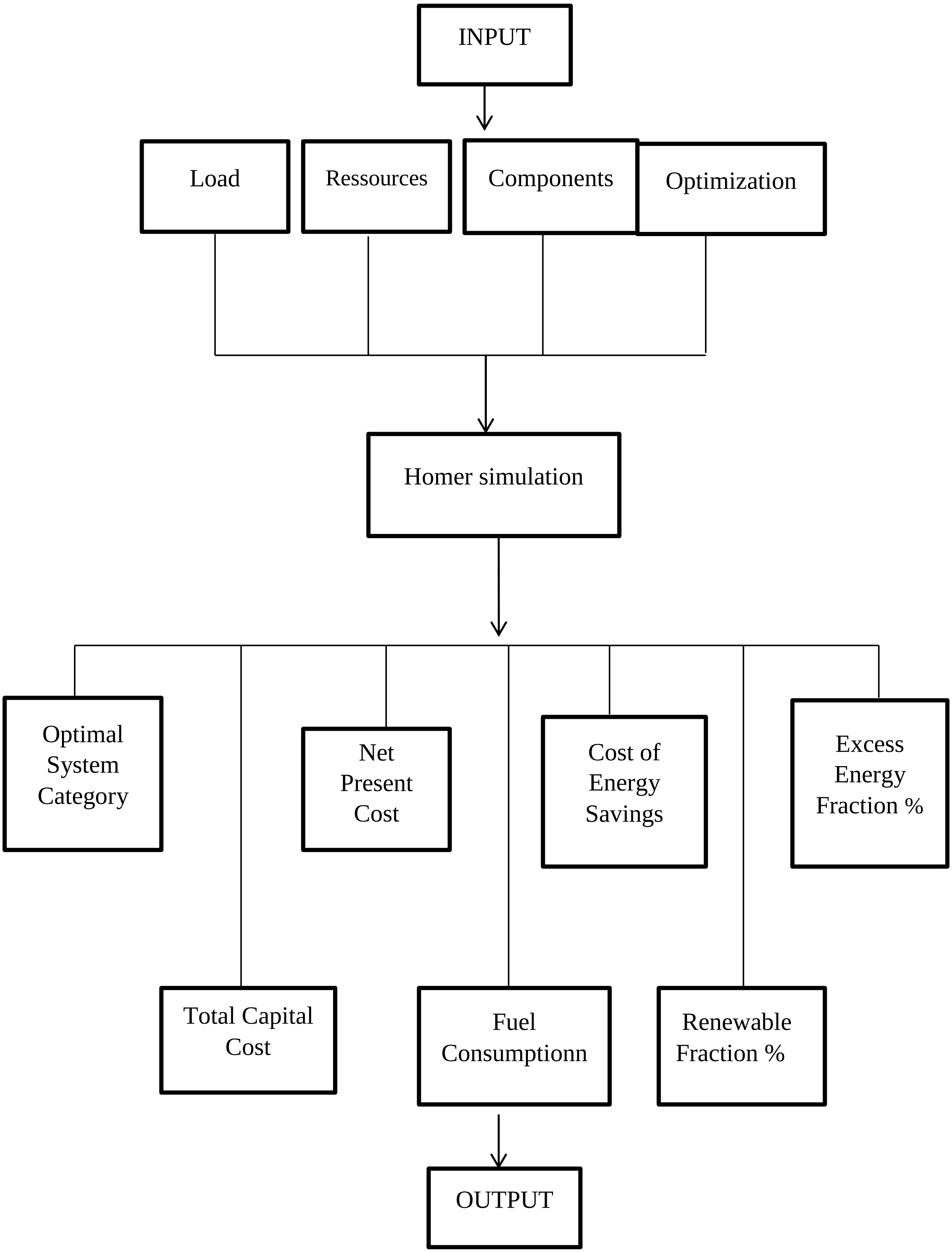

Figure 2.19: Architecture of HOMER software

Source: (Erdinc & Uzunoglu, 2012)

2.7.4 Technical-economic analysis study

2.7.4.1 Sizing methodologies

In the field of IRES based power generation, various sizing Methodologies have been reported in literature such as artificial Intelligence, multi objective design, analytical approach, iterative technique, probabilistic approach, graphical construction method, commercially available computer tools. At present, there is no simple method to determine the best combination of HRES that is well suited for a particular application due to the complexity and diversity of hybrid energy systems. The only way to seek solution to this problem is by modeling the HRES.

2.7.5.1 Estimating Solar PV output

The performance of the PV system decreases with increase of ambient temperature and the accumulation of dust on the solar panels (desert regions). The power output and the efficiency of the PV panel are given by Equation 1 and equation 2 respectivelly (Ghenai & Janajreh, 2016).

$$P_{PV} = Y_{PV}.f_{PV}\left(\frac{G_T}{G_{T,STC}}\right)\left[1 + \alpha_p.(T_C - T_{C,STPC})\right] \qquad \text{Equation 1}$$

$$\eta_{mp,STC} = \frac{Y_{pv}}{A_{PV}.G_{T,STC}} \qquad \text{Equation 2}$$

Where $\mathbf{P_{PV}}$ is the power output of the PV array in kW

$\mathbf{Y_{PV}}$ is the rated capacity of the PV array (power output under standard test conditions kW)

$\mathbf{f_{PV}}$ is the de-rating factor (account for soiling of the panels, wiring losses, shading, and aging), $\mathbf{G_T}$ is the solar radiation incident on the PV array in the current time step [kW/m^2]

$\mathbf{G_{T,STC}}$ is the solar radiation at standard test conditions [kW/m^2]

$\boldsymbol{\alpha_p}$ is the temperature coefficient of power [%/°C],

$\mathbf{T_C}$ is the V cell temperature at the current time step [°C], and

$\mathbf{T_{C,STPC}}$ is the PV cell temperature under standard test conditions [25 °C]

$\mathbf{A_{PV}}$ is the surface area of the solar PV

2.7.4.2 Estimating Biomass gasifier output

Presently, biomass gasifier based power generation system is a mature technology for electrification of isolated areas. In biomass gasification, producer gas is generated when biomass is burned with insufficient oxygen. The generated producer gas is mixed with diesel in certain ration and used in diesel engine that runs coupled generator to produce electricity. The hourly electrical power output of biomass gasifier system depends on biomass availability and generator operating hours per day. Mathematical model of biomass gasifier System is represented as follows (Chauhan & Saini, 2014).

$$P_{BMGS} = \frac{\text{total biomas available}\left(\frac{\text{tonnes}}{\text{year}}\right) * CV_{BM} * \eta_{BMG} * 100}{365 * 860 * (\text{operaing hours per day})} \qquad \text{Equation 3}$$

Where P_{BMGS} is hourly output of biomass gasifier system, CV_{BM} is calorific value of biomass (4015kcal), η_{BMG} is the overall conversion efficiency of the biomass gasifier system from biomass (fuel wood) to electricity production (21%).

The hourly power output of biogas based system depends on biogas generation per day and operating hours of alternator in a day. The mathematical model for biogas based power generation system is represented as follows

$$P_{BMGS} = \frac{\text{total biogas generated}\ (m^3/\text{day}) * CV_{BG} * \eta_{BGGS}}{860 * (\text{operating hours/day})} \qquad \text{Equation 4}$$

Where CV_{BG} is calorific value of biogas (4700 kcal), η_{BGGS} is the overall conversion efficiency of biogas system from biogas to electricity production (27%).

Annual energy production of a biomass gasifier based system can be estimated as:

$$E_{BMGS} = P_{BMGS}(365 * 24 * \text{capacity factor}) \qquad \text{Equation 5}$$

2.7.5 Economic and financial criteria of optimal hybrid energy systems

For unit sizing and cost optimization of IRES, HOMER makes economic analysis and ranks the system according to NPC. In economic analysis, parameters like net present cost (NPC), levelised cost of energy (LCOE), annualized cost of system $C_{ann,tot}$, payback period (PBP), internal rate of return (IRR) etc. are considered by various authors (Chauhan & Saini., 2014).

2.7.5.1 Levelized cost of energy (LCOE)

Levelized cost of energy (LCOE) is the average cost/kWh of useful electrical energy produced by the system (Nigussieet al, 2017). LCOE includes all recurring and non-recurring costs over project lifetime. It is defined as the ratio of the total annualized cost of system $C_{ann,tot}$ to the annual electricity production (E_{total}) by the system. Mathematically, it can be estimated using Equation 6.

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{total}} \qquad \text{Equation 6}$$

2.7.5.2 Annualized system cost

Annualized system cost is the sum of the annualized cost (capital, replacement and maintenance) of all the system components.

2.7.5.3 Net present cost

Net Present Cost (NPC) is the value of the cost of installing and operating the system over the lifetime of the project (also referred to as lifecycle cost) (Nigussie et al., 2017) . It comprises all costs and revenues that occur within the project lifespan which includes the initial capital cost of the system components, cost of any component replacements that occur within the project lifetime, cost of maintenance, fuel cost, and cost of purchasing power from the grid.

The NPC is given by Equation 7.

$$\mathrm{NPC} = \frac{C_{ann,tot}}{CRF_{(i,Rproj)}} \qquad \text{Equation 7}$$

Where:

$C_{ann,tot}$ is the total annualized cost

i is the annual real interest rate (discount rate),

Rproj represents the project lifetime,

and CRF is the capital recovery factor, given by Equation 8.

$$CRF_{i,N} = \frac{i(1+i)^N}{[i(1+i)-1]} \qquad \text{Equation 8}$$

Where

i: the annual real interest rate

and N is the number of years.

2.7.5.4 Internal rate of return

The internal rate-of-return (IRR) is the true interest yield offered by the system during its operational period. It is also referred to as there turn on investment (ROI) or the time-adjusted rate-of-return. It is evaluated by calculating the discount rate that results the net present value (NPV) of the project to be equal to zero

2.7.5.5 Payback period

This is the time period during which the initial investment (cash outflow) of the system is expected to be recovered from the investment generated cash inflow.

2.7.5.6 Simple Payback period

The payback period is the number of years required for the investment to be recovered.

2.7.5.7 Renewable fraction

Renewable energy fraction of a system is defined to be the total annual energy production that is drawn from renewable energy sources and is calculated by dividing the amount of annual renewable power production by the total annual energy production (Dalton et al., 2008; Dekker et al., 2012). A higher the renewable energy fraction will allow a better reliability of the system.

CHAPTER 3

CHAPTER 3

3. MATERIALS AND METHODS

3.1 Introduction

In this section of the study, the data collection method, technical parameters, components, materials and preliminary design of the system to meet the village load will be discussed. The study uses secondary data on rice production from existing studies in the region (Nygaard et al., 2016) and pre-feasibility study for an electric power plant based on rice straw (Fock, 2012). Environmental data such as ambient temperature, relative humidity and cloudiness were obtained from NASA database online. Electricity demand information was obtained through a field survey in the village. The specification and cost information on the system components were obtained at through question submitted to suppliers.

3.2 Study area

Sokolo is a small town and rural community in the town of Niono in the Region of Ségou Southern-Central Mali, with coordinates 6° 07′ 18″ West and 14° 44′ 17″ North (Figure 3.1). The village is situated on approximately 2,219 Km² in the north of Mali in Segou Region near the border with Mauritania. With a population of 22,310 inhabitants in 2017. The village essentially thrives on agriculture (mainly rice), livestock and trading activities. The village has some administrative and social infrastructures such as a Sub-Prefecture, a City Hall, a Community Health Centre, mosques, schools, fuel stations, etc. In addition to these, there are shops for sewing, carpentry, and stores etc. The choice of sokolo for this study is due to the high demand of electricity from the community and mostly due to its location in the office du Niger .There is a lot of potential in the village of Sokolo, as a major rice growing community. The availability of rice straw potential could help with power generation from biomass. The village is also close to a high voltage transmission line, which will allow for the transport of excess energy from the plant (Nygaard et al., 2012). There is electricity demand from households and commercial activities (AMADER, 2017).

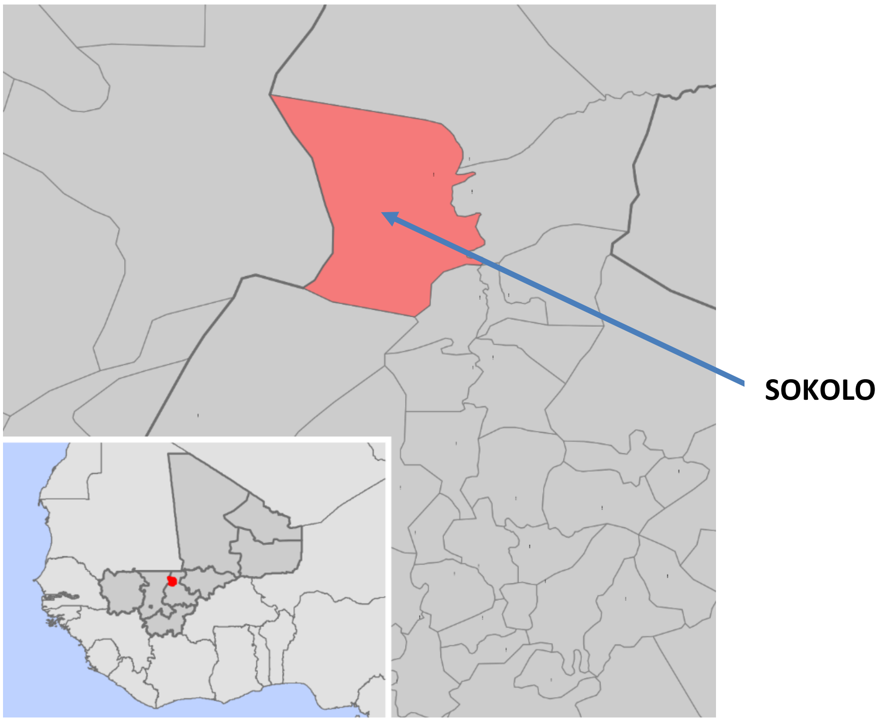

Figure 3.1: Map showing location of Sokolo

3.3 SOKOLO's energy situation

The energy situation in sokolo is like in any other sub-Sahara African rural areas. The village previously had a hybrid power plant manage by AMADER composed of a diesel generator which gave electricity to the village of sokolo since 2012. Due to the instability in the northern region of Mali, the plant has not been operating. Some wealthier population in the village have solar home systems to satisfy their electricity needs.

3.4 Methodology

In order to design micro solar-biogas battery hybrid power system, one has to provide some inputs such as hourly load profile, available biomass (tonne/day), cost of biomass, monthly solar radiation, value for a PV system, the initial cost of each component (such as renewable energy generators, diesel generators, battery, converter), cost of diesel fuel, annual real interest rate, project lifetime, etc. (Nigussie., 2017). The load profile of the village was determined by using the wattage and hour of use of proposed equipment. The design of hybrid renewable energy system (HRES) must be optimal in order to supply electricity reliably and economically. The configuration of the components in the hybrid system is optimized in order to minimize the LCOE.

3.4.1 Energy System Modelling Components and Sizing (HOMER input data)

Sokolo is a place endowed with several renewable energy resources. Choice of the optimum solution was made from many system configurations on technical, economic and social basis. System analysis with HOMER requires information on the resources, economic constraints, and control methods. Input information included design variables like PV array size, convertor size, quantity of battery, average solar radiation, biomass availability for gasifier-generator unit for power generation. The Solar/battery storage /biomass-biogas generator configuration shown as Figure 3.2. The proposed system consists of PV modules, batteries, charge controller, converter, and biogas generator. The energy system modelling was performed with HOMER in order to study the technical economic and social feasibility of the system. HOMER performs the calculations and displays the results. Thus, the final solution may be chosen from the optimal solutions, and also considering the solutions that have not been selected as optimal solutions. In HOMER, the best possible or optimal system configuration is the one that satisfies the constraints of the lowest net present cost and the lowest levelized cost of energy LCOE. The schematic diagram for optimized Solar-Biomass gasifier design in HOMER is shown in Figure 3.2.

The main requirements for system design are:

- The site information, such as solar intensity, ambient temperature, relative humidity and cloudiness.
- The electrical load information such as the load type and time of use of electrical appliances.
- The specifications and cost information of solar panel, battery, inverter, charge regulator.

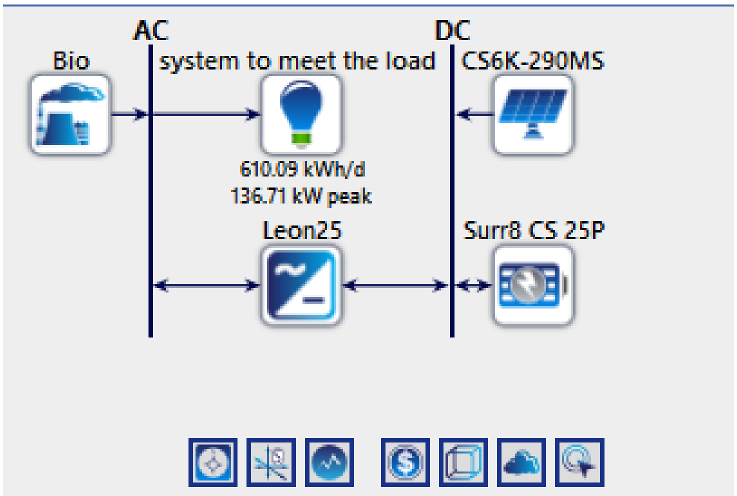

Figure 3.2: hybrid system configuration simulated with HOMER

3.4.2 Scenarios

The design criteria was for the system to be technically, economically and socially feasible. Wind and hydropower were not considered because of the low potential of wind resource in the region and use of water for irrigation farming purposes. The scenarios considered are shown in Table 3.1.

Table 3.1: Scenarios considered for performances analysis

Scenarios	Details
A	Standalone Biomass generator
B	Biomass generator/ solar PV/ battery/converter
C	Diesel generator /solar PV/ battery/converter
D	Solar PV/ battery/converter

3.4.3 Village electrical load profiles estimation

In HOMER, the term load refers to a demand for electric or thermal energy. The load profile of the village determined by using the wattage and hour of use of typical electric equipment that is supposed be used in rural areas. The village is composed of 710 households, the electric demand of the community is divided in to the following categories: administrative load (and a city hall, household/domestic sector, community health centre load, 35 Commercial loads or small businesses, 3 schools (2 elementary and a secondary school); 4 cult load (religious demand comprising 3 mosque and a church) and community load which consists of some 3 flour mills. The total electric load estimated for the listed appliances above was summed up to get the required load. A detailed description of the appliances is found in Appendix 1.

3.5 System designing

3.5.1 Solar PV

To model Solar PV a system array with Homer, the data on solar resource for the location is needed, HOMER runs based on directly imported solar resources from the NASA surfaces Methodology and Solar Energy database by entering the GPS coordinates. A phone GPS was used for the location measurement. Direct Normal Radiation (DNR), Clearness Index, Monthly Average Air Temperature and Monthly Averaged Relative Humidity are shown in Table 3.2.

Table 3.2: Global horizontal solar radiation data Sokolo

Location Sokolo Lat 14.739 /Lon 6.118 Averaged Direct Normal Radiation (kWh/m2/day), y Averaged Clearness Index, Monthly Averaged Air Temperature at 10 m Above the Surface of the Earth (°C), Monthly Averaged Relative Humidity (%), (22-year Average).				
	DNI	Clearness index	Air temperature	Relative humidity
Jan	6.7	0.58	21.9	15.7
Fev	7.47	061	24.1	12.5
March	6.87	0.62	28.6	13.2
April	7.44	0.63	31.5	22.9
May	7.21	0.62	30.9	43.7
Jun	7.21	0.61	28.6	61.1
July	6.11	0.61	26.1	74.8
August	5.34	0.60	25.6	74.6
September	5.72	0.58	26.8	66.5
October	6.75	0.58	28.7	33.8
November	7.3	0.59	26.5	12.4
December	6.49	0.61	22.8	16.3

3.5.2 Solar PV module types and cost

In this study the CS6K-295MS Canadian Solar 295W Mono-crystalline PV module with 60 mono-crystalline cells is selected, with a lifetime of 25 years. The detailed specifications and the I-V characteristics of the module at different insulations and temperatures are shown in Table 3.3 (Canadian Solar, 2014). The cost of solar PV modules is dependent on factors such as the size of panel, type of technology (mono or polycrystalline), the brand manufacturer, the retailer and country in particular. The initial capital cost of solar energy (plus Installation costs) for a 1 kW solar energy systems was found to be US$ 1200 and the replacement cost was also considered equal cause it is considered that the entire unit will be replaced in case of replacement. These prices are likely to vary from the actual system quotes due to many market factors (which are, dealer's profit mark-ups, size of the solar panel, technology, the brand etc.), and are therefore only indicative. No tracking system was assumed for the PV system to avoid additional cost. The derating factor accounts for effects of dust on the panel, wire losses, elevated temperature, or anything else that would cause the PV array output to deviate from that expected under ideal conditions is estimated to be 88% and the efficiency 18.02%.

Table 3.3: Technical specification of SUPERPOWER CS6K- 295 MS

Parameters	Specification
General information	
Technology	Mon-crystalline (Mono)
Dimensions	65.00 x 39.10 x 1.57 inches
Cell Arrangement:	60 (6x10)
Electrical data	

Nominal Maximum Power (Pmax):	295 Watts
Optimum Operating Voltage (Vmp):	32.30 Volts
Optimum Operating Current (Imp):	9.14 Amps
Open Circuit Voltage (Voc) :	39.50 Volts
Short Circuit Current (Isc) :	9.75 Amps
Module Efficiency:	18.02%
Operating Temperature	-40°C ~ +85°C
Max Series Fuse Rating:	15 Amps
Power Tolerance:	0 ~ + 5 W
Temperature Characteristics	
Temperature Coefficient (Pmax)	-0.39 % / °C
Temperature Coefficient (Voc)	-0.30 % / °C
Temperature Coefficient (Isc)	0.053 % / °C
Nominal Operating Cell Temperature	45±2 °C

3.5.3 Converter/inverter

Since the hybrid energy system comprises both AC and DC systems from biogas generator and solar PV arrays respectively, a power converter system is required to convert DC output from the PV to AC to be used in the system. A power converter maintains the flow of energy between the AC electrical load and DC components of the hybrid energy system and charges the storage batteries (Adaramola et al., 2015) . A power electronic converter is needed to maintain the flow of energy between the AC and DC buses. Costs of inverters and control chargers vary based on their sizes. For this study, Leonics S219CPH 5 kWh 48 DC model of converter is selected. The lifetime assumed for the converter is 10 years. For a 1 kW of converter the system initial and replacement cost was considered to be US$ 810 (plus installation). The technical specifications of this inverter are shown in the Table 3.4[1].

Table 3.4: Technical specifications for converter/inverter

Parameters	Specification
Rated Power	5.0 k VA / 5.0 kW
Max. power at 25°C for 1 hour	5.5 kW
Nominal Voltage	48 Vdc
Maximum charging current	60 A
Frequency	50 / 60 Hz ± 3 Hz
Max. AC current (for charge mode)	22.7 A
AC OUTPUT	
Maximum AC current	22.7 A
Maximum surge current	200%
Maximum charging current	60 A
Maximum AC current	22.7 A
Efficiency Inverter peak efficiency	> 96%

3.5.4 Storage Batteries

Generally, batteries are used for energy storage purpose, to store excess power from renewable energy systems necessary to meet power demand when the energy generators (PV, wind, generator etc.) produce excess energy. That energy stored will be used when the systems are not producing enough power to meet the demand at peak time when there are not producing at all intermittency time. For this study, the storage battery selected is the Surrette 6CS25P from the manufacturer Rolls/Surrette. It has dual case replaceable cells and an expected life of over 10 years. The selected battery has the following characteristics obtained from HOMER modeling tool in Table 3.5. The capital cost of the selected battery was taken to be US$ 350 per unit of battery, with a maintenance cost of US$ 10/ year.

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[1] Details available from www.leonics.com

Table 3.5: Technical specifications for Rolls Surrette 6CS25P (6-CS-25P) battery

Nominal capacity	1150 Ah (6.91 kWh)
Maximum charge current	279A
minimum state of charge	40%
Efficiency	80 %
Maximum discharge current	279 (A)
Nominal voltage	6 (V)
Capacity ratio	0.478/ hr.

3.5.5 Biomass / Rice straw input estimation for the system analyze

HOMER biomass resource inputs allow the modeler to specify the availability of the feedstock throughout the year, and to model explicitly the feedstock conversion process. Users can indicate the availability of biomass feedstock by importing an hourly data file or using monthly averages. The user must specify four additional parameters to define the biomass resource: price, carbon content, gasification ratio, and the energy content of the biomass fuel (Lambert et al., 2006). In this study Gasification is used to convert rice straw/husk to synthetic gas (biogas). The gas derived from biomass is used as the primary fuel for the generators. Capital cost of the biogas system is the sum of the capital cost of the gasifier and the capital cost of the biogas generator. For this study, the biomass resource used in the simulation was using some assumption in the next section /day from January to December (constant supply of biomass to generate the biogas fuel to run the generator) will be determined in the following section.

Availability factor for the sustainable resource in the business-as-usual (BAU) and realist scenario was set at 15% of the straw that is currently burned in the fields. For the optimistic scenarios, the fraction currently incorporated into the ground is also included. This makes the availability factor for the optimistic scenario equal to 30% (Nygaard et al., 2016). As biomass is considered as a no or fuel cost crops, the cost of collection and transportation of rice straw will be considered as $50 / tonne. . Operating lifetime was also considered 20,000 h. From the literature review the technical potential of rice straw and husk has been calculated. Rice production is a seasonal crop in the village of sokolo. According to their two farming programs in office du Niger: the normal period of farming in Mali is from July to October and the “hors season “referring to this program the office du Niger’s administration releases water from farms. Recording rice residues availability according to this program can be uncertain and not accurate so for this study the potential of rice residue for biomass production will is taken from the FAO (FAOSTAT, 2016). The technical potential will be considered to be the average production from 1961-2016.

Table 3.6: Theoretical potential of rice straw and husk for biogas production in sokolo

Production Mali (tonnes/yr)	Segou	sokolo	RPR	recoverability fraction	theoretical potential
Straw					
2780905	723035	24751	0.75	0.3	5569
Husk					
2780905	723035	24751	0.25	0.3	1856

3.5.6 Diesel Generator

The lifetime of a generator depends strongly on the hours of operation and the fuel characteristic. Diesel generator initial costs vary with the size, the model and the design. In this study, ideally the biogas genset with a capacity of 150-200 kW would be selected to cover a peak load of 153.31 kW. The initial capital cost of the biogas generator was assumed $352/kW. Replacement and operational costs were assumed to be equal to the initial capital cost. Operating lifetime was also considered 20,000 h.

Diesel fuel price

The diesel generator system is used to supplement the power production. The diesel fuel price in Mali according to the global market price is US$ 1.1 per litre ($1=555.00 CFA) as of June 18, 2017 (GlobalPetrolPrice.com, 2018). However, in remote areas, diesel prices may be significantly higher than that of the official price, due to transportation and other ancillary costs. In this study, the diesel generator characteristic will be considered equal to the characteristic of the biomass generator. The capital initial cost and the replacement cost were considered to be US$ 352. And the maintenance and operation cost was taken US$ 0.03/ hours.

3.5.7 Hybrid System Control Parameters and Constraints: (other inputs)

Mali is a member of the Economic and Monetary Community of West Africa (UEMOA). In UEMOA, interest rates decisions are taken by the Central Bank of West African States' Monetary Policy Com mittee. The interest rate is 4.5% as of April 2018; the annual real interest rate is taken to be 8%. The project life has been considered to be 25 years. The maximum annual capacity shortage is taken to 0% since the power system is required to meet the daily electric load demand throughout the year without shortage The physical and thermal properties of rice waste was obtained from (Yu et al., 2016) as follows: Lower heating value (MJ/Kg) =14.40, Carbon (wt.%) = 32.22, Hydrogen (wt.%) = 5.83, Oxygen (wt.%) = 38.58, Nitrogen (wt.%) = 0.65 and Sulphur (wt. %) = 0.23. Summary of Technical and financial input data required for designing, stimulation and optimization is shown in Table 3.7.

Table 3.7: Summary of Technical and financial input data required for designing, stimulation and optimization

Homer inputs				
System Component	Capital initial (US$)	Replacement	O&M	Quantity
Solar PV	352	352	10	0.295 kW
Converter/inverter	810	810	10/yr	1 kW
Battery	350	350	10/yr	Unit
Diesel generator	352	352	0.03/hrs	1 kW
Biogas generator	800	800	0.03/hrs	1 kW

CHAPTER 4

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Introduction

The chapter presents the summary of the technical simulations performed using Homer software for the study area. The implementation priorities of the systems which depend on the economics and the sustainability factor are given with a performance and resilience analysis for the best economic and sustainable scenarios. It presents and discuss the results based on different scenarios and their feasibility.

4.2 Electricity demand

The electrical load requirement of the village was done through field survey of household energy consumption patterns in the village and by approximation using typical remote village appliance (energy efficient appliances), typical village energy usage durations was assumed for the community. Community load was considered to be to two types; primary and deferralable loads. Primary loads are those that must be meet immediately (lighting, cooking, radio, etc.) and deferrable loads are electric demand that can be served at any time within a certain time span (water pump, etc.), regulates the demand profile and has a control on the electricity cost, also it considered that the village will not need any deferralable loads, in the future for community water pumping. The daily electricity demand was estimated to be approximately 600 kWh/d with peak load of 160 kW between 7-10 pm. During the evening, the villagers are all at home and almost all the appliances are being used. The village daily load profile is illustrated in Figure 4.1. The village electrical load is divided into the following categories: administrative load of 9.04 kWh/d, school load of 0.9 kWh/d, community health center load of 4.1 kWh/d, small businesses load of 18.1 kWh/d, household load of 200.85 kWh/d, and the remainder for cult and community loads.

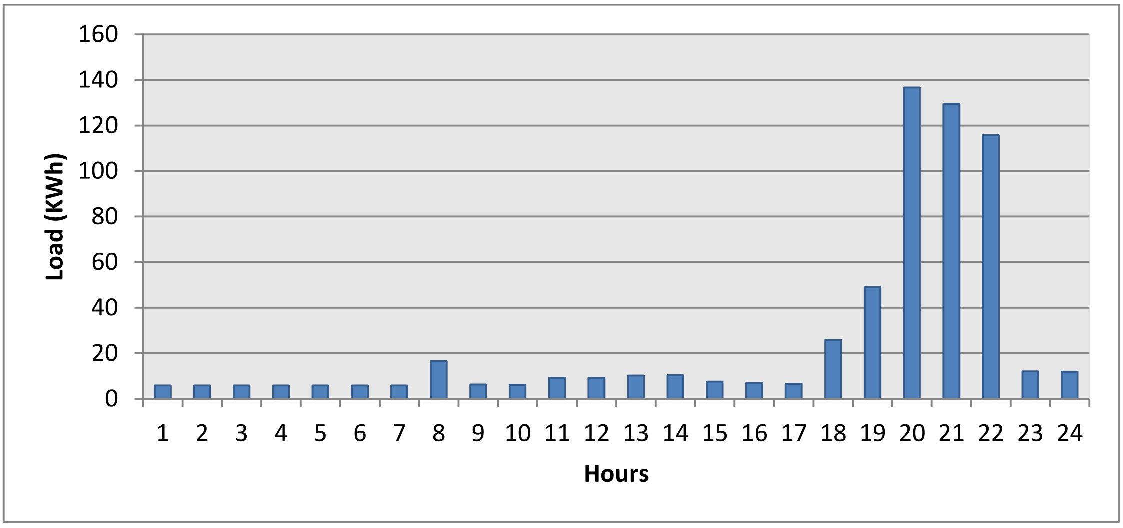

Figure 4.1: Sokolo's daily load profile

4.3 Presentation of the scenarios performance

In this section, each scenario will be presented, from Scenario A to Scenario D. The system with the least NPC and cost of energy, the least capacity shortage and excess power production, higher renewable energy fraction and lowest fuel consumption would be chosen as optimum. All the scenarios were optimized using the same data set, but with different renewable energy (components) combinations.

4.3.1 Scenario A performances (biomass only)

In Scenario A, the load of the village will be met with a single energy system, a biogas generator as shown in Figure 4.2.

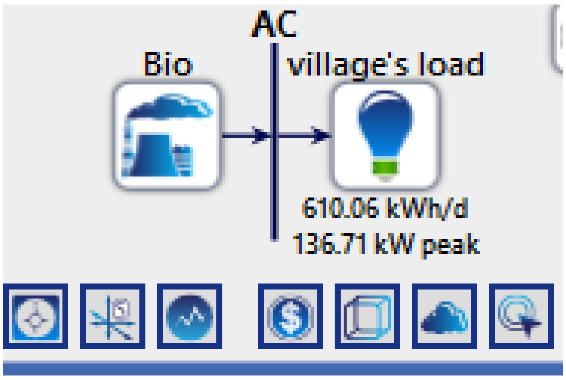

Figure 4.2: Schematic of Scenario A

Based on the energy and economic parameters as well as assumptions used in this study, NPC and LCOE generated are US$ 3,508,888 and US$1.22 per kWh, respectively. System architecture results are indicated in Table 4.1. Supplying the village load with the scenario A would require a high biomass resource. Other economic indicators of this present system are shown in Figure 4.3.

Table 4.1: System architecture for Scenario A

Architecture		Cost $					System
Bio (kW)	Dispatch	LCOE $	NPC $	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Production (kwh)
200	LF	1.218958	3,508,888	25,9051.1	160,000	100	905,901

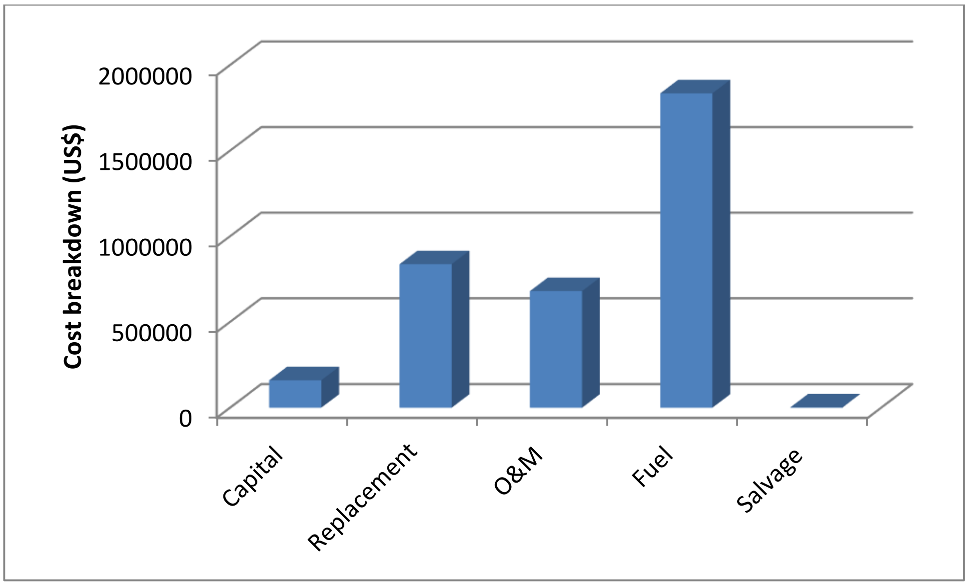

Figure 4.3: optimisation results for scenario A

The total electrical production available to meet the village demand in Scenario A is 905,901 kWh/yr, deliverd by the biogas generator. Only 222,672 kwh/yr from that production is consumed by the AC primary Load. The system generates 683,229 Kwh/yr of excess representing 75.4% of the total production as shown in Table 4.2. The system biogas consumption is equal to 2,839 tonnes/year.

Table 4.2: Biogas and power generation details in scenario A

Parameter	Value
Total production	905,901 kwh/yr
AC primary load	222,672 kwh
Excess electricity	683,229kwh/yr -75.4%
Renewable fraction	100%
Hours of production	8,760 hrs/yr
capacity factor	51.7%
Electrical production	905,901 kwh/yr
mean electrical output	100kw
Fuel consumption	2,839 tonnes/yr
Mean electrical efficiency	11.3%

4.3.2 Scenario B performances (biomass/ solar PV/ battery)

In scenario B the load will be met by a hybrid renewable energy system (HRES). The proposed system consists of biomass generator, solar PV modules, converter, and storage batteries in case of excess energy production to be used at peak consumption. The systems will require biomass resources and solar as feedstock for the various technologies. The schematic of and detail of the scenario in Figure 4.4.

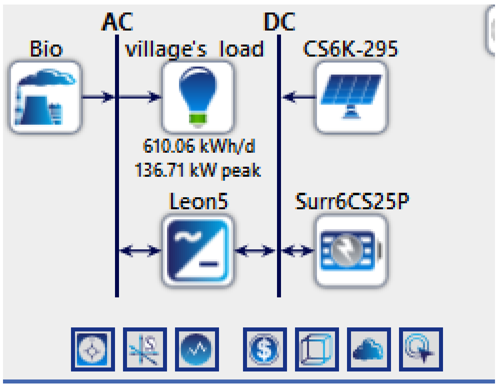

Figure 4.4: Details of Scenario B

This system also has a renewable fraction of 100% made possible through usage of solar and biomass resources only. The Net Present Cost (NPC), Levelized Cost of Energy (LCOE) and other parameters are shown in Table 4.3. The system architecture is composed as follows: solar PV 100kW, biomass generator 150 KW, batteries 610 kWh and 30kW of converter. Detailed cost of the system is shown in Table 4.4.

Table 4.3: Optimised results for scenario B

Architecture(kW)				Cost($)				System	
PV	Bio	Battery	Con	COE	NPC	Operating cost ($/yr)	Initial capital ($)	Re-Frac (%)	Total Fuel (L/yr)
100	150	133	30	0.279	804,174	38,213.21	310,172	100	416.421

Table 4.4: Detailed costs for Scenario B

component	capital cost $	Replacement $	O&M $	Fuel $	Salvage $	total $
solar pv	119,322.03	0.00	43,822.09	0.00	0.00	163,144.12
biomass genset	120,000.00	55,137.29	85,515.52	269,164.77	4,671.38	525,146.20
converter	24,300.00	21,467.53	3,878.25	0.00	2,910.63	46,735.16
battery	46,550.00	22,683.58	51.58	0.00	136.67	69,148.49
System (TOTAL)	310,172.03	99,288.41	133,267.45	269,164.77	7,718.68	804,173.98

The total electrical production available to meet the village load is deliverded by the biogas generator and solar PV. Sscenario B produces is 134,723 kWh/yr with biomass contributing

55.3 % and solar energy contributing 44.7%. The system produces 58,294 Kwh/yr of electricity excess representing 19.3% (see Table 4.5 for details). Scenario selected system has a capacity shortage equal to 0 Kwh/yr. The excess of energy creates unnecessary initial capacity cost and increases the cost of energy but will be available to support possible load increase in the village.

Table. 4.5 Electrical production parameters in scenario B

Parameter	Value
Solar PV production	166,895kWh/yr -55.3%
Biogas genset production	134,723 Kwh/yr – 47.3%
Ac primary load consumption	222,672 kWh/yr - 100 %
Excess of electricity	58,294 kWh/yr - 19.3 %
Renewable energy fraction	100%
Solar output	
Total production	166,895 kWh/yr
Capacity factor	19.1%
Mean output	19.1kw
Levelized cost	0.0756$/kWh
Biomass output	
Hours of operations	1,470 hrs/yr
Number of starts	373 starts /yr
Electrical production	134.723 kWh/yr
Fuel consumption	416 tonne/yr
Capacity factor	10.3%

4.3.3 Scenario C performances (diesel generator / solar PV /battery storage)

Scenario C represent a hybrid system composed of conventional diesel generator, solar PV modules, system converters and storage batteries. This scenario is similar to what pertains today in Malian rural electrification through AMADER and its collaborators, a schematic presenting scenario C can be found on Figure 4.5.

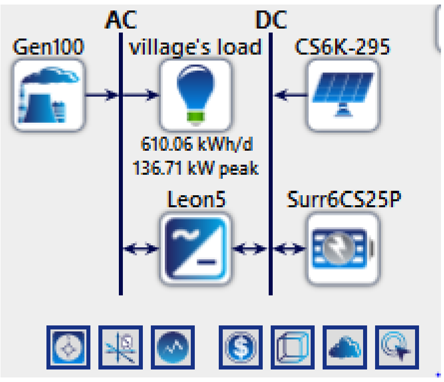

Figure 4.5: Details of Scenario C

The categorized optimization result of all the promising configurations of feasible power scheme to supply the village load with scenario C are listed in Table 4.6, with NPC of US$ 930,883.3 and LCOE of US$ 0.323. Scenario C has a renewable fraction of 57.9%, with the following architecture: 100 kW solar PV, 100 kW diesel generator, and 3070 Ah batteries.

Table 4.6: System architecture for Scenario C

Architecture (kW)				Cost($)				System	
PV	Diesel	Nb Bat	Convert	LCOE	NPC	Operating ($/yr)	Initial	Ren Frac (%)	Total Fuel (L/yr)
100	100	444	50	0.3233811	930883.3	44916.69	350222	57.88	27813.28

The system economic breakdown by components is summarized in Figure 4.6. The cost breakdown in scenario C shows that more than half of the system capital cost ($ 115,400.00) is consumed by the storage system, followed by the solar modules ($119,322.03), the converter ($40,500) and diesel generator ($35,000.00. Diesel generators also appear to be a cheap technology, only diesel fuel cost makes its integration into hybrid mini grid costly.

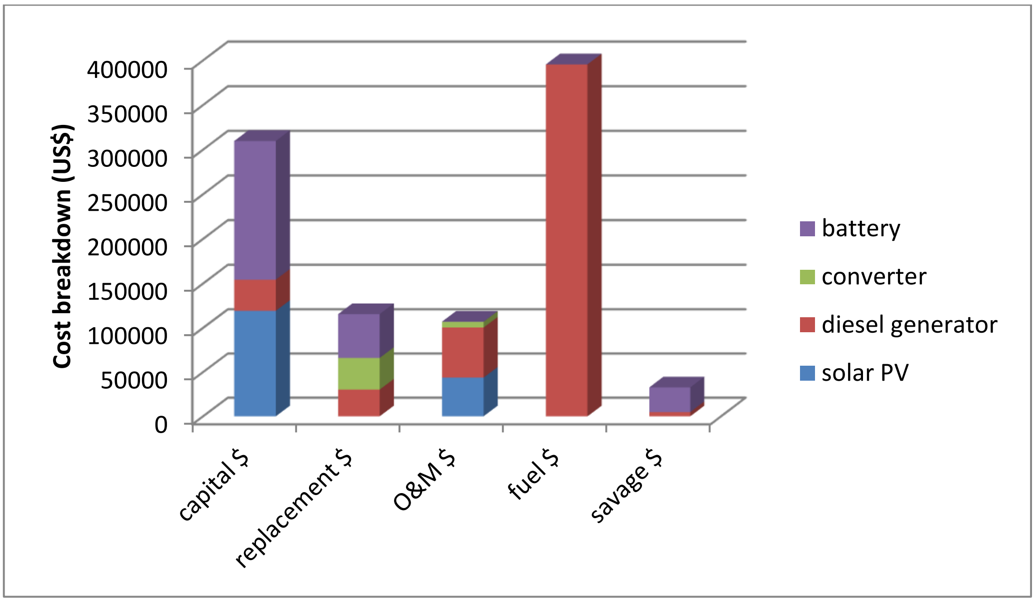

Figure 4.6: System cost summary

Scenario C based has a total production of 260,671 kWh/yr where 166,895 kWh/yr representing 64% of the production is from solar energy and 260,671 kWh/yr representing 36% is from the diesel generator. About 222,672 kWh/yr of the power production is consumed in AC load. Renewable fraction of the system is 57.9% (see Table 4.7).

Table 4.7: Electrical production parameters for scenario B

Parameter	Value
Solar PV production	166,895kWh/yr (64%)
Diesel generator	93,776 kWh/yr (36%)
AC production consumption	222,672 kWh/yr
Excess electricity	9,435 kWh/yr (3.62%)
Renewable energy fraction	57.9 %
Capacity shortage	139 kWh/yr-0.0625%

4.3.4 Scenario D performances

In scenario D the load will be with a solar system. The proposed system consists of solar PV, storage batteries and converter. The schematic of and detail of the scenario in Figure 4.7.

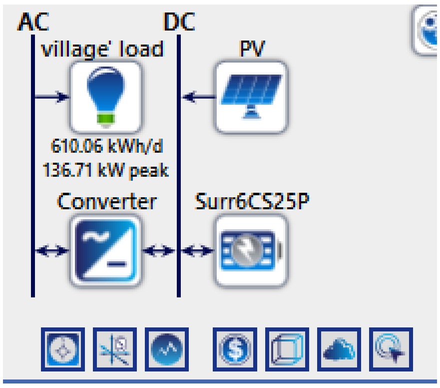

Figure 4.7: Schematic of Scenario D

The optimized results for scenario D is presented in Table 4.8, NPC of US$ 888

44*77ù239.13 and LCOE of US$ 0.23814. It consists of the following architecture: 200 kW solar PV, 3600 Ah batteries and 150 kW of converter. Cost breakdown is shown in Figure 3.8. The total cost is the sum of all the other costs of the component: solar PV module represents the component with the highest cost followed by the DC to AC converters.

Table 4.8: Scenario D system architecture and summary cost

Architecture				Cost/				System
PV (kW)	Battery	Converter (kW)	Dispatch	LCOE ($)	NPC ($)	Operating ($/yr)	Cost/Initial capital ($)	Re Fra (%)
200	520	150	CC	0.23814	888239.1	20656.94	542144.1	100

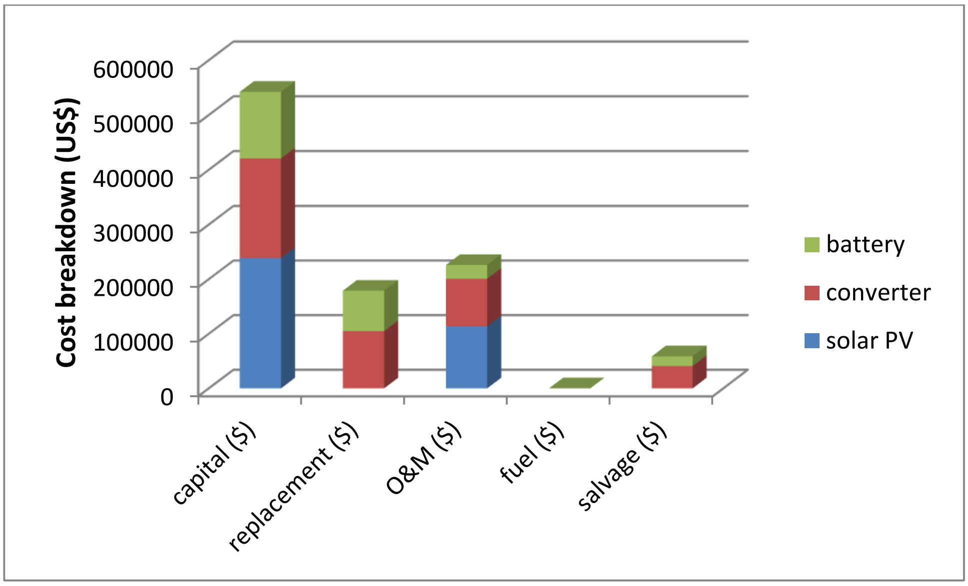

Figure 4.8 : Scenario D cost breakdown

The only generation technology in Scenario D is the solar PV modules. The total production from the PV array is 350,458 kWh/yr. the system also generates an excess energy of 19.9% (see Table 4.9). The PV panel starts generating for the system form sunrise to sun set and it also charge the batteries to be used in the evenings.

Table: 4.9 Technical details of scenario D

Parameter	Value
Solar PV production	350,458 kWh/yr- 100%
AC primary load consumption	222.622 kWh/yr
Excess	69,660 kWh/yr -19.9%
Unmet electric Load	49.9 0 kWh/yr -0.022%
Capacity shortage	209 kWh/yr-0.0940 %
Total production	350,458 kWh/yr
Capacity factor	20%
Hours of operation	4.432 Hrs/yr
Levelized cost	0.0600 $/kWh

4.1 Summary results from the scenarios

As shown in Table 4.10, the system with the least NPC is Scenario B, and that with the least LCOE is Scenario D. It is also necessarily considered in early stage of a project, as it measures the excess or shortfall of cash flows, in present value terms, once financing charges are met. NPC is often used to assess the feasibility of an energy project by investor. LECO is criteria that allow to evaluate systems economic performance from the viewpoint of consumers. The system design is for the people living in rural areas with low incomes and should therefore be affordable.

Table 4.10: scenario evaluation criteria

Parameter	Scenario A	Scenario B	Scenario C	Scenario D
NPC	3,508,888	804,174	930,883	888,239.10
LCOE	1.22	0.279	0.323	0.238

4.2 Multi-criteria decision making

This section of the work describes the application of Multi-Criteria Decision Making (MCDM) technique for selecting the best energy scenario among the four scenarios designed to meet the energy demand of the village of SOKOLO. They are evaluated according to technical, environmental and economic criteria, with sub-criteria including Renewable energy fraction, Excess electricity produced, fossil fuel used, emissions initial cost, levelized cost of energy , Return on Investment and Simple payback time. The Technic of order Preference by Similarity Ideal Solution (TOPSIS) considers three types of attributes or criteria to evaluate energy systems or technologies: Qualitative benefit criteria, Quantitative benefit criteria and Cost attributes. Each sub-criterion is assigned to a specific criterion and their corresponding study references. The benefit attributes used for the analysis are: Negative: ‘less is better’; Positive:’ more is better’ (See Appendix 2 for the details).

4.2.1 Weight of sub criteria

The priority is given to the environment criteria. A scenario which will be able to produce electricity in a sustainable way and solve the problem of agricultural waste management is preferred. The weight was assigned based on perception, as there is no published criteria for this particular study. Weights assigned are shown in Table 4.11 and the analysis is shown in Table 4.12.

Table 4.11: Weights assigned for analysis

Sub-criteria	Weights
Scenario’s efficiency	0.015
Reliability	0.075
Maturity	0.095
Resources availability	0.092
RE-fraction	0.093
Emission CO2	0.15
Total fuel	0.09
Excess electricity	0.02
Initial capital cost	0.09
Net present cost	0.11
Savage	0.02
LCOE	0.15

Table 4.12: TOPSIS Analysis

	Technical criteria				Environment criteria				Economic criteria			
Weight	0,015	0,05	0,072	0,09	0,093	0,15	0,09	0,09	0,095	0,15	0,02	0,085
Sub-criteria	Scenario's efficiency %	Reliability	Tech maturity	Resources availability	RE-fraction	Emission CO2	Total fuel	Excess electricity	Initial capital cost	Net present cost	Savage	LCOE
Scenario A	40	40	7	40	100	3342	2839	75,4	160000	4E+06	1916	1,22
Scenario B	70	90	8	60	100	490	4166	19,3	38213	804174	7719	0,279
Scenario C	80	60	8	40	57,6	72748	278133	3,62	350222	930883	37523	0,323
Scenario D	90	90	8	90	100	0	0	19,9	542144	888239	6E+06	0,238

Summary of results

scenario A	0,538095
scenario B	0,914044
Scenario C	0,424745
scenario D	0,772054

TOPSIS selects the alternative that is closest to the positive ideal solution and farther from negative ideal alternative. The relative closeness to the ideal solution for energy scenario selection for the rural community of sokolo using MCDM TOPSIS approach is presented in detail in Appendix 2. After using MCDM TOPSIS approach to evaluate the available scenarios to meet the energy demand for the village Scenario B was the best optimum solution (91.14%) followed by scenario D (77.20%), A (53.80%) and C (42.24%). These results can vary with different weight selections. In this analysis, priority was given to the environmental criteria which disadvantaged scenario C because it uses a conventional generation technology in its design.

4.2.2 Scenario B versus scenario C (the selected scenario / AMADER's model)

CO2 emissions CO2

Renewable energy are clean and emit little or no pollutant that could be harmful for then for the environment the selected system B composed only renewable energy generating technologies it can be it that like it can be seen in table 4.13. these emission are consider to be neutral cause (of utilization of rice straw) the plant is supposed to have observed more than the amount emit during growing phase on the other hand the system employed by AMADER which is a mix of conventional and power generation technologies has a high emission of pollutant 72748kj/ yr of carbone dioxide and 495kj/yr of Carbone monoxide.

Table 4.13 pollutants emission form the systems

	System B	System C
Carbone dioxide kj/yr	429	72,748
Carbon Monoxide kj/yr	0.728	495
Unburned Hydrocarbons kj/yr	0	20
Particulate Matter kj/yr	0	1,98
Sulphur Dioxide kj/yr	0	178
Nitrogen Oxides kj/yr	0.455	39.6

4.2.3 Economic analysis of the scenario B versus C

Referring to figure and figure 4.11and 4.12, were it possible to see the detail cash flow of both system throughout the 25 year of the programs lifetimes. The cash flow chart in the systems doesn’t vary much form one to the other. System B is a lower cost of project while system C showed better saving option on solar energy component system which means that scenario B or C the implementation prices are practically the same then B could replace AMADER scenario without a problem.

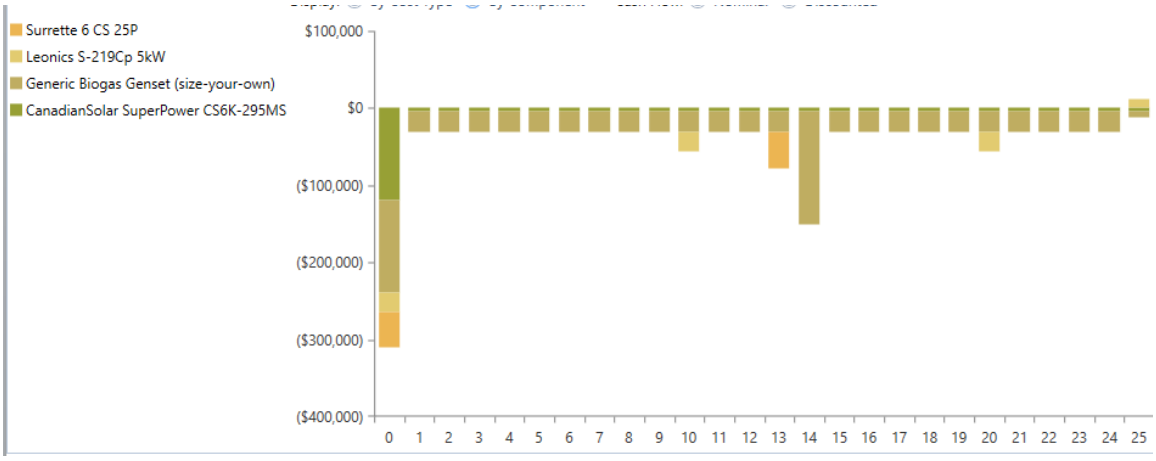

Figure 4.9: cash flow by component system B

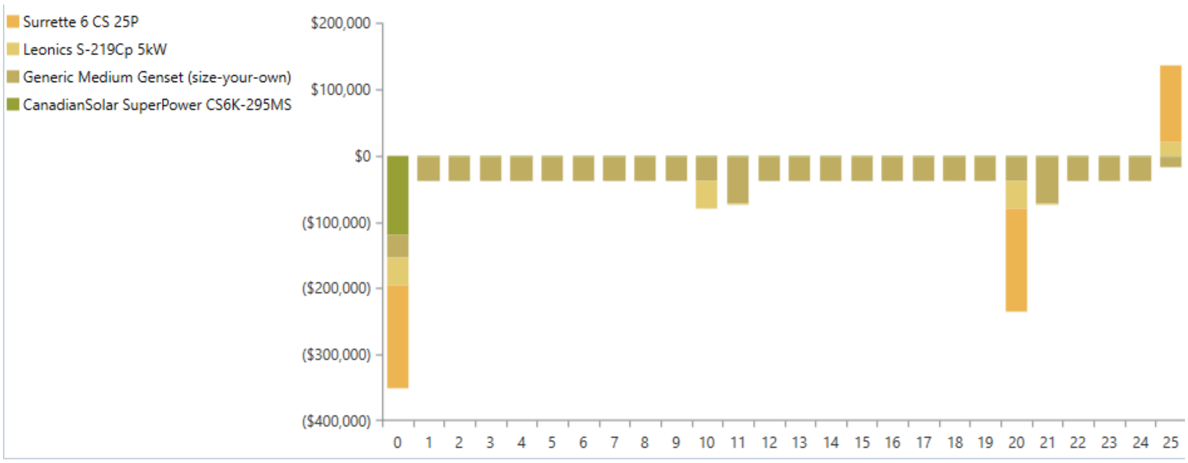

Figure 4.10 cash flow by component system C

4.2.4 Sensitivity analysis for the selected scenario

The sensitivity analysis aimed to show how results obtained from simulation and optimization in the chosen scenario ‘B’ varies with changes in unpredictable inputs, such as fuel costs, solar radiation, biogas generator capital cost, and price of biomass feedstock. As shown in Figures 4.11and 4.12, as the capital cost multiplier increase from 1 to 3, the cost of energy vary from 0.279 $/kW to 0.362 $/kW. The same thing is observed for an increase in the capital cost multiplier of the biogas generator. As it increases from 1 to 3, the cost of energy also increase from 0.279$/kW to 0.446 $/kW. The increases of these capital costs increase the total net present cost of the system from US$ 804,174.00 to US$ 1,282,818.00. Thus, an increase in the capital cost of the PV and the biogas generator or other system components will lead to the system becoming expensive and perhaps unaffordable for the community and so unattractive to investors (See Appendix 3 for the biomass price and interest rate effect on the NPC and LCOE).

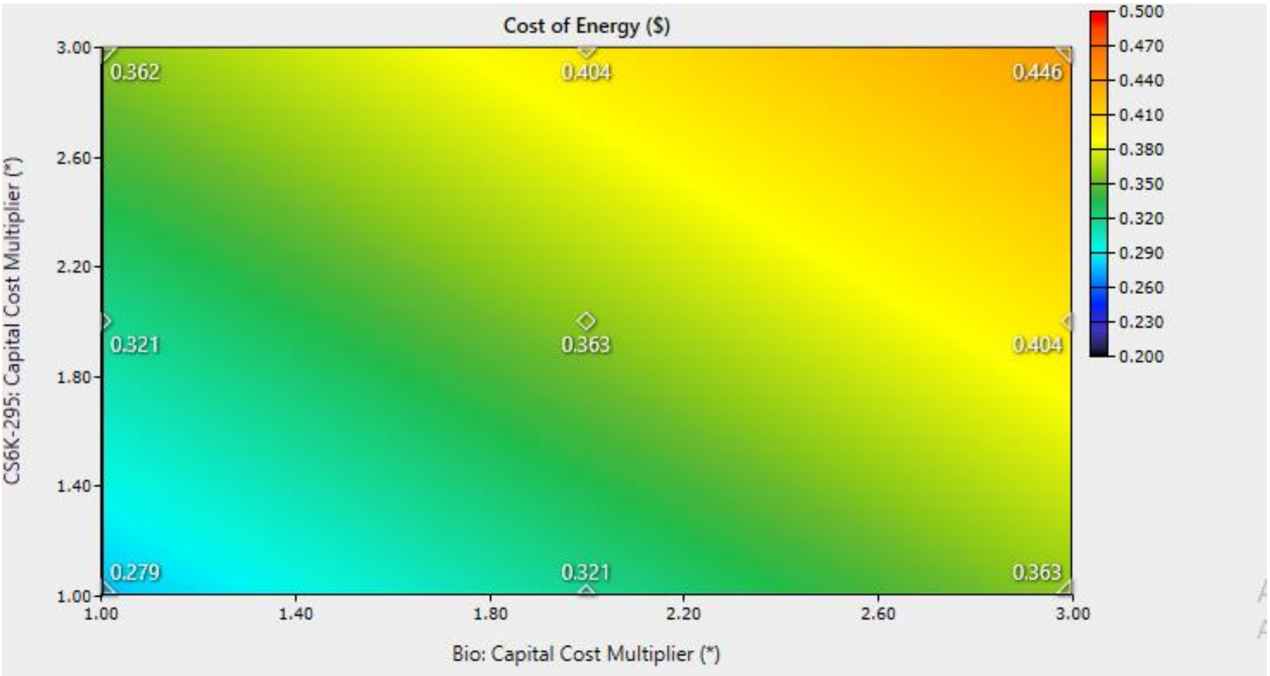

Figure 4.11: Effects component solar PV and biogas generator cost multiplier on the system LCOE cost of energy

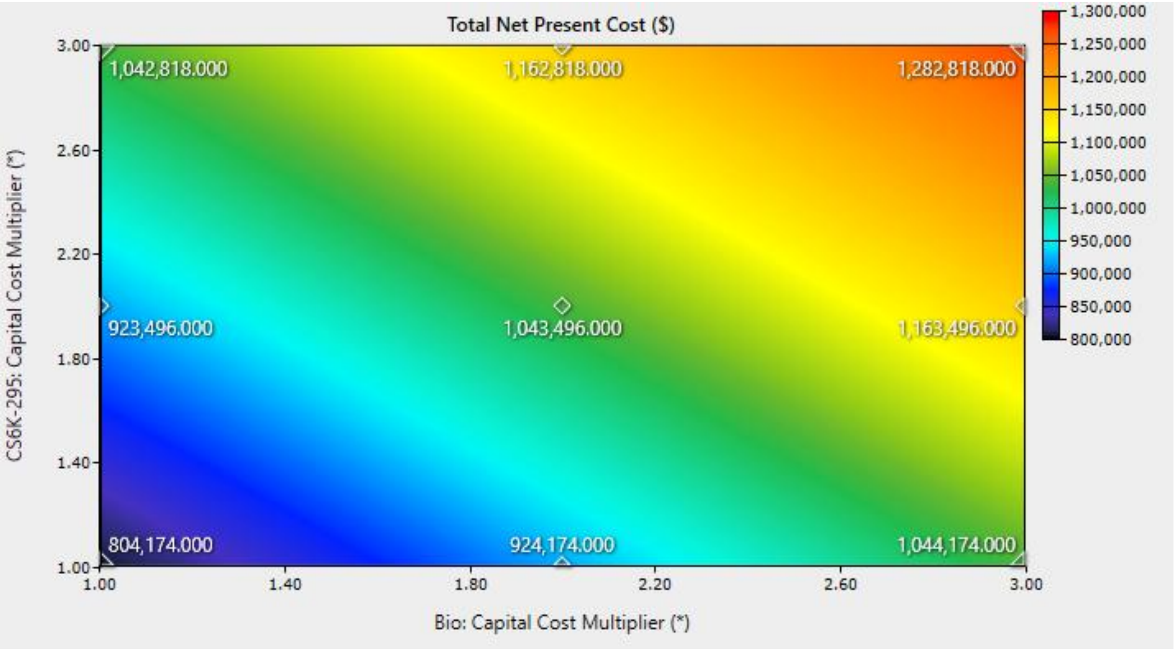

Figure 4.12 Effects component solar PV and biogas generator cost multiplier on the total net present cost of the system

CHAPTER 5

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The aim of this was to design a hybrid renewable energy (HRES) system for the Sokolo community and find solution for agriculture residue disposal. HOMER Software was used to perform the analysis to find a suitable hybrid system for the community. Four systems were analyzed and the most feasible was selected according to techno-economic and environmental criteria and by evaluation of renewable energy fraction, net present cost, levelized cost of energy and greenhouse gas emission, for the different scenarios. The study uses secondary data on rice production (The technical potential of crop residues) from existing studies in the region and pre-feasibility study for an electric power plant based on rice straw. Environmental data such as ambient temperature, relative humidity and cloudiness were obtained from NASA Surface Meteorology Database online. Electricity demand information was obtained through a field survey in the village. The specification and cost information on the system components were obtained at through question submitted to suppliers. The most optimal system of a hybrid biogas generator/ solar PV modules / battery storage /converter was found to be composed of 100 kW of solar PV array, 150 kW biogas generator 920 Ah of battery capacity and 30kW of converter to meet a total load of 610 kWh/day and a peak load 136.71 kW. The LCOE of the selected system is US$ 0.279 /kWh, with a NPC of US$ 804,174, a CO_2 emission of 490 kg/yr., a simple payback time of 8 years and a renewable energy fraction of 100%. This study concludes that agricultural residue can be incorporated in electricity generation and lead to affordable and environmentally friendly and cost competitive supply of electricity and increase electricity access in rural remote areas. In Malian context after comparing the feasible system to the model used in rural electrification program it appeared that this present model would have a huge impacted economically for the rural population and could prevent the emission of 72748kj/ yr of Carbone dioxide and 495kj/yr of Carbone monoxide from the environment.

5.2 Recommendations

Rice straw and other agricultural processing waste offers a potential feed stock for the production of electricity and other fuels. Utilization of these residues can help improve energy supply and reduce the generation of gases from decayed agricultural waste. It is recommended that the use of agricultural waste for electricity generation is included in rural electricity generation program in Mali. It is recommended that data gathering is enhanced for effective planning of biomass and other renewable energy system.

Studies on the criteria and weight distribution is needed for effective evaluation of the scenarios

Future studies should consider using ground measurement for more accuracy in solar radiation measurements

Further studies can also evaluate urban Municipal solid waste and animal manure potential always in the purpose of domestic energy efficiency and enhance energy access in rural ad peri-urbain areas of the country

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APPENDIXES

Appendix 1:

Load estimation details

Load Category	appliances	Quantity	wattage (w)	Usage hr/d	Usage hr/d	AC load wh/d	Total category Load /d
administrative (2)	lamp	20	15	8:00-17:00	9	2700	
	fan	8	30	14:00-17:00	3	720	
	printer	2	60	12:00-13:00	1	120	
	office desktop	2	60	10:00-12:00	2	240	
	Photocopier	2	60	12:00-12:30	0,5	60	
	fridge	2	100	00:00-00:00	24	4800	
	fountain	2	100	12:00-14:00	2	400	9040
schools (3)	Lamp	6	15	08:00-09:00	1	90	
	fan	3	30	14:00-17:00	3	270	
	office desktop	3	60	12:00-14:00	2	360	
	printer	3	60	12:00-12:30	0,5	90	
	Photocopier	3	60	12:00-12:30	0,5	90	900
community health centre (1)	lamp	11	15	19:00-23:00	4	660	
	fan	2	30	14:00-17:00	3	180	
	microscope	2	15	12:00-14:00	2	60	
	x-ray machine	1	100	12:00-14:00	2	200	
	office desktop	1	60	12:00-14:00	2	120	
	fridge	2	60	00:00-00:00	24	2880	4100
small business (35)	Lamp	35	15	18:00-22:00	4	2100	

	fan	15	30	12:00-14:00 19:00-21:00	4	1800	
	fridge	5	100	00:00-00:00	24	12000	
	Radio	10	15	12:00-14:00 19:00-21:00	4	600	
	TV	5	80	19:00-21:00	4	1600	18100
households (710)	Lamp	3550	12	18:00-22:00	4	170400	
	fan	1420	30	19:00-22:00	3	127800	
	Radio	710	15	07:00-08:00	1	10650	
	TV	300	80	19:00-22:00	3	72000	
	fridge	50	100	00:00-00:00	24	120000	
	phone	100	6	22:00-00:00	4	2400	500850
cults (4)	Lamp	16	15	14:00-16:00	2	480	
	fan	8	30	14:00-16:00	2	480	
	radio/micro	2	15	14:00-16:00	2	60	1020
community load (3)		3	1000	10:00-14:00	4	12000	12000
				Safety load		10%*548410	603251
					Total load	610kwh/d	

Appendix 2: TOPSIS Analysis Details

Technical Criteria

Criteria	No	Sub-criteria	Benefit attribute
TECHNICAL	1	Scenario’s efficiency	Positive
	2	Reliability	Positive
	3	Maturity	Positive
	4	Resources availability	Positive

Environmental criteria

Criteria	No	Sub-criteria	Benefit attribute
Environmental	1	RE-fraction	Positive
	2	Emission CO2	Negative
	3	Total fuel	Negative
	4	Excess electricity	Negative

Economic criteria

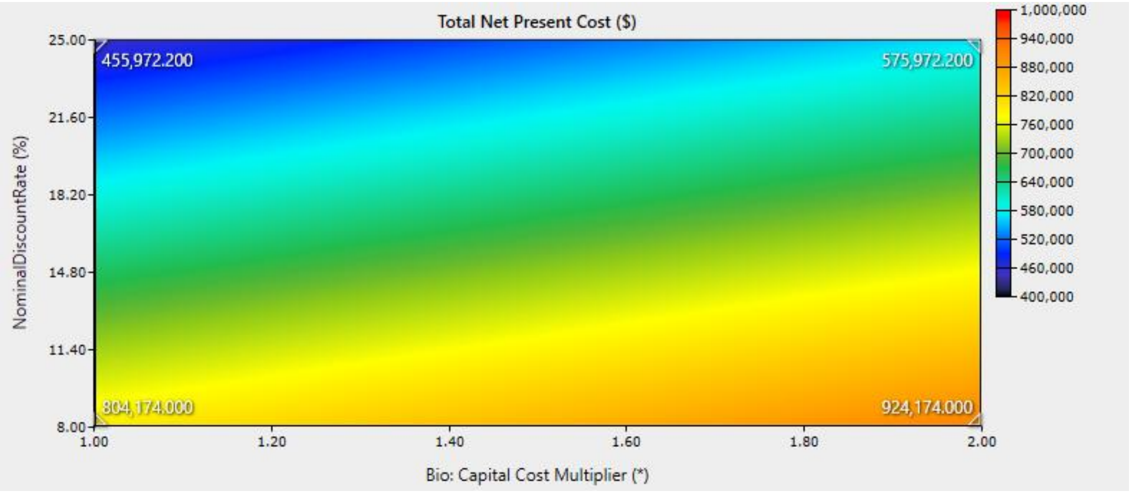
Criteria	No	Sub criteria	Benefit attribute
Economic	1	Initial capital cost	Negative
	2	Net present cost	Negative
	3	Savage	Positive
	4	LCOE	Negative

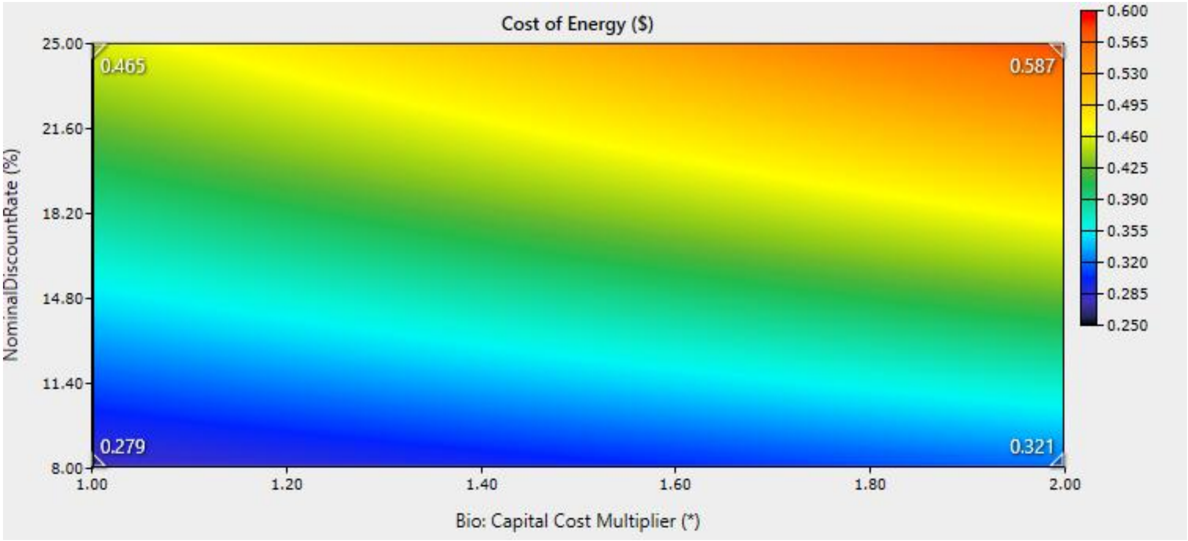
Technical weights Application of TOPSIS model to rank the best scenario to meet the loads

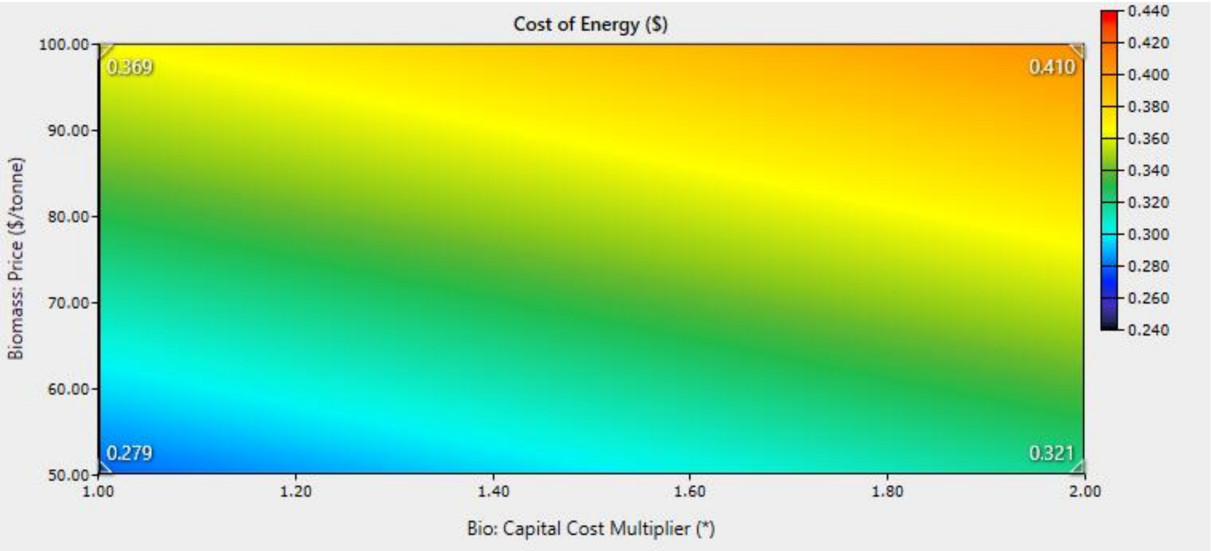
Scenario	Scenario’s efficiency	Reliability	Tech Maturity	Resources availability
A	Low	Low	High	Low
B	High	Highest	High	Moderate
C	Highest	Moderate	High	Low
D	Moderate	High	High	Highest

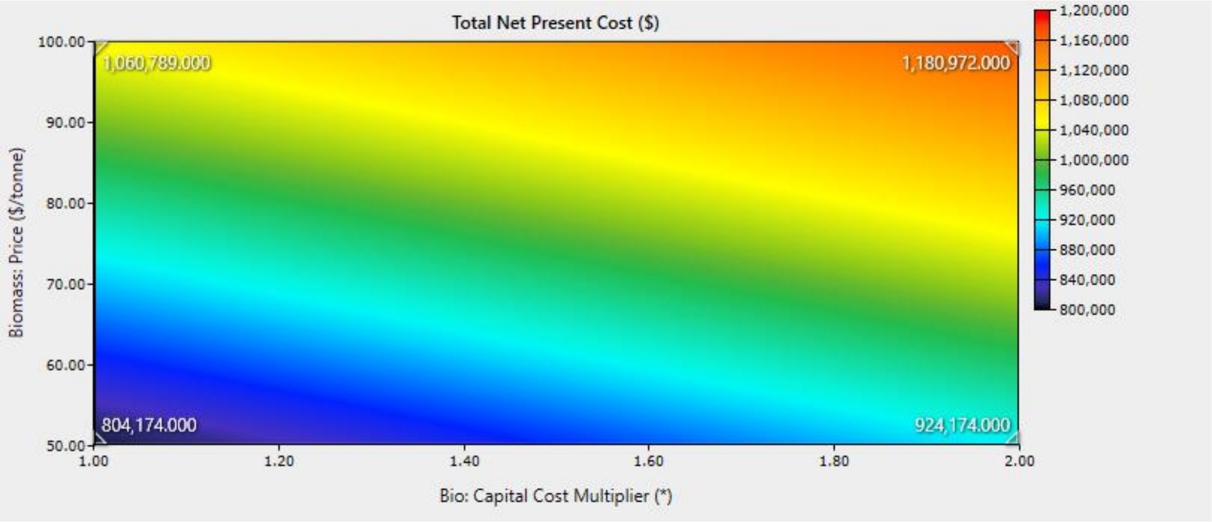
Appendix 3: Other Sensitivity Results

Effects of different variables on NPC and LCOE






Cost of Energy ($)
Biomass: Price ($/tonne)
100.00
90.00
80.00
70.00
60.00
50.00
Bio: Capital Cost Multiplier (*)
1.00
1.20
1.40
1.60
1.80
2.00
0.369
0.410
0.279
0.321
0.440
0.420
0.400
0.380
0.360
0.340
0.320
0.300
0.280
0.260
0.240


Total Net Present Cost ($)
Biomass: Price ($/tonne)
100.00
90.00
80.00
70.00
60.00
50.00
Bio: Capital Cost Multiplier (*)
1.00
1.20
1.40
1.60
1.80
2.00
1,060,789.000
1,180,972.000
804,174.000
924,174.000
1,200,000
1,160,000
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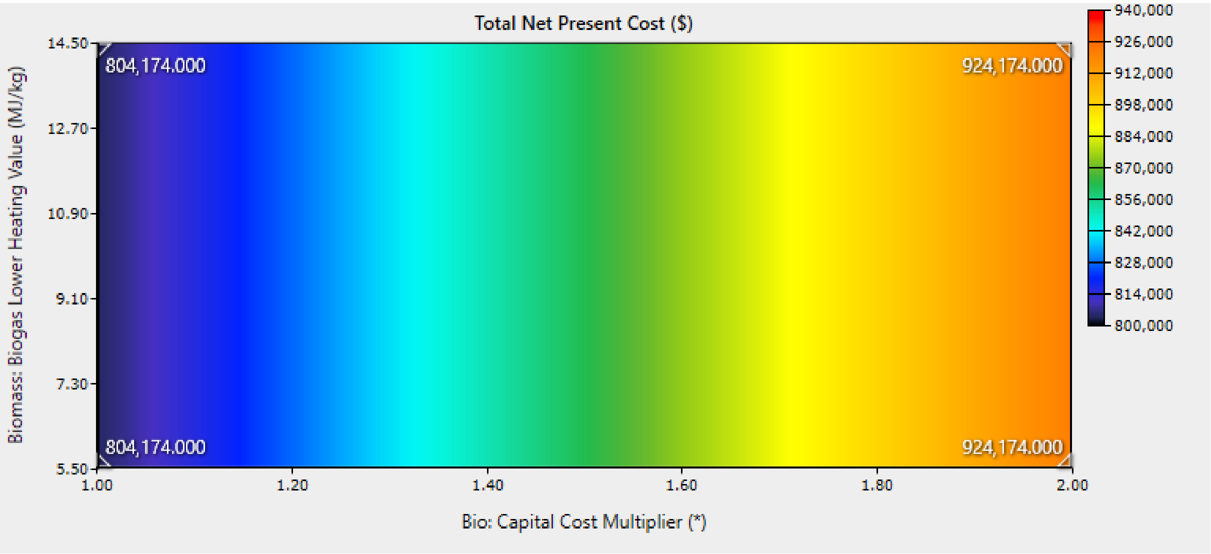
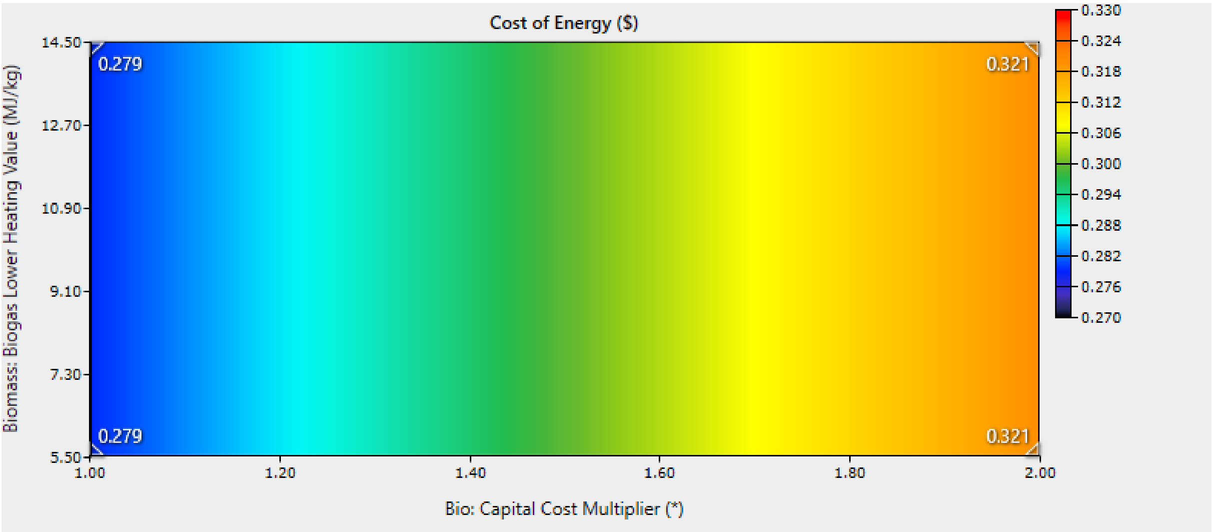
920,000
880,000
840,000
800,000


Total Net Present Cost ($)
Biomass: Biogas Lower Heating Value (MJ/kg)
14.50
12.70
10.90
9.10
7.30
5.50
Bio: Capital Cost Multiplier (*)
1.00
1.20
1.40
1.60
1.80
2.00
804,174.000
924,174.000
804,174.000
924,174.000
940,000
926,000
912,000
898,000
884,000
870,000
856,000
842,000
828,000
814,000
800,000


Cost of Energy ($)
Biomass: Biogas Lower Heating Value (MJ/kg)
14.50
12.70
10.90
9.10
7.30
5.50
Bio: Capital Cost Multiplier (*)
1.00
1.20
1.40
1.60
1.80
2.00
0.279
0.321
0.279
0.321
0.330
0.324
0.318
0.312
0.306
0.300
0.294
0.288
0.282
0.276
0.270