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Prospects of distributed electricity generation and services based on small scale biomass systems in Ghana

by

Pol Arranz Piera

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Doctoral Thesis

Prospects of distributed electricity generation and services based on small scale biomass systems in Ghana

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PhD Supervisor

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Barcelona, September 2018

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PROGRAMA DE DOCTORAT EN SOSTENIBILITAT

ÀMBIT D'ENGINYERIA INDUSTRIAL

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THESIS ABSTRACT

Access to clean energy is crucial to human welfare, no residential, commercial or industrial activity can be conceived without energy supply. At the same time, current dependence on fossil fuels and their negative effects on global climate claim for urgent alternatives.

The situation in Sub-Saharan Africa is poignant: over half of the population, mainly in rural areas, live without access to electricity and modern energy services. However, crop residues from farming communities in those areas are unused and remain available for valorisation. While technology for electricity production from agricultural biomass is progressing, managing decentralised rural electricity projects is still a challenge, especially in developing countries like Ghana, given the variety and complexity of the factors conditioning biomass to energy supply chains. Such complexity has been previously formulated in academic exercises, but with limited practical applicability for energy planners, practitioners and investors.

This research has put effort in deploying a holistic approach to sustainable biomass-to-energy planning, yet flexible to adapt to different regulatory scenarios and energy supply configurations. A qualitative framework has been developed to characterise the planning of decentralised power generation and subsequent service schemes based on agricultural biomass residues. The framework takes into consideration four critical components: social development component, organisational/institutional component, technical component, and financial component, with their respective metrics. Then, the framework has been applied to three real case study configurations in Ghana, involving primary data collection via field surveys, sustainability modelling and discussion of the techno-economic feasibility results with policy makers and practitioners.

The first configuration consists in decentralised power generation using crop residues from smallholder farms within defined clusters in 14 administrative districts in Ghana, where surveys have been conducted, residue-to-product ratios determined in farmer fields and thermochemical characterisation of residues performed in the laboratory. The number of clustered farms, reference residue yields, and residue densities were determined to assess the distances within which it would be feasible to supply feedstock to biomass power plants. The findings show that in most districts, a minimum of 22 to 54 larger (10 ha) farms would need to be clustered to enable an economically viable biomass supply to a 1000 kWe plant. Financial analyses for a 1000 kWe CHP plant case indicate that such investment would not be viable under the current renewable feed-in-tariff rates in Ghana; increased tariff by 25% or subsidies from a minimum 30% of investment cost are needed to ensure viability using internal rate of return as an indicator. Carbon finance options are also discussed.

The second configuration is focused on cogeneration and trigeneration from clustered agricultural residues. Techno-economic results show that 600 kW and 1 MW CHCP plants run on local agro residue to generate power, heating (for cassava or maize drying) and cooling (to refrigerate tomatoes) are feasible in certain rural districts, considering a minimum 20% yearly profit for investors' equity. Crop residue biomass could generate additional income for farmers in the range of 29 to 64 US $/tonne of crop residue if a minimum of 60% of the heat produced can be traded. The consideration of carbon financing under the most common prices currently traded in existing carbon funds has little impact on the preliminary project results; however, if more favourable schemes (like the Swedish carbon tax) are considered, the viability of cogeneration and trigeneration plants run on agro residue can be possible even with a low level of residual heat sales.

The third configuration analyses minigrid electricity generation and services based on agricultural residue gasification in five Ghanaian communities. Results show that the projected electricity demand of the communities compares favourably with the potential energy generation from available agricultural residues, a situation that we envisage in many rural communities where agriculture is a predominant livelihood activity. As with most biomass electricity analysis, it is not profitable from the perspective of an entrepreneur with 100% private funding; however, by applying a customer tariff equal to the current expenditure on electricity equivalent uses in the communities, a subsidy of about 35% on initial investment would enable a private entrepreneur an internal rate of return of 15%, whereas a 60% subsidy could enable internal rate of return of 25%.

The outcomes of this research have been considered by stakeholders in Ghana within the formulation of rural electrification policies and regulations, and the prospects of trigeneration and biomass minigrids have also triggered the interest of Ghanaian and international private investors.

Keywords

Rural electrification, Biomass Mini-grids, Agricultural residues, Energy planning, Feasibility studies, Ghana.

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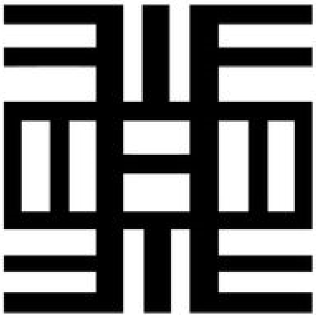
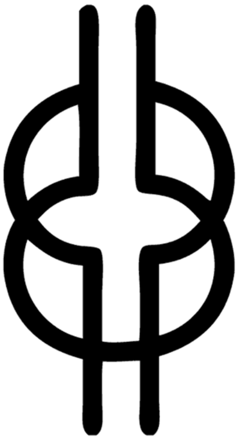


NEA ONNIM NO SUA A, OHU

"She/He who does not know can know from learning" symbol of knowledge,
life-long education and continued quest for knowledge



NYANSAPO

"Wisdom knot" symbol of wisdom, ingenuity, intelligence and patience. An especially revered symbol of the Akan culture (Ghana), this symbol conveys the idea that "a wise person has the capacity to choose the best means to attain a goal. Being wise implies broad knowledge, learning and experience, and the ability to apply such faculties to practical ends."

(Willis, "The Adinkra Dictionary", www.adinkra.org)

Die Philosophen haben die Welt nur verschieden interpretiert,
es kömmt aber darauf an, sie zu verändern

"Philosophers have only interpreted the world in various ways; the point, however, is to change it"

Karl Marx, Thesen über Feuerbach**.** Stuttgart, 1888

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First and foremost, I want to thank my supervisor, Prof. Enrique Velo, for his trust, guidance and respectful support throughout all these years, and for his permanent commitment to improving education on clean energy. *Moltes gràcies!*

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I would also like to thank all the staff from the University Research Institute for Sustainability Science and Technology (IS.UPC), and the financial support received from the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), the UPC Centre for Cooperation for Development (CCD) and the European Commission (DEVCO-EuropeAid).

This research would have never been possible without the inspiration and teachings from my colleagues and mentors at TTA in Barcelona (Xavier, Jaume, Christoph), Ecuador (Santiago, Patrick), former students at UPC (and great professionals today, Maria Anzizu, Joan Cortés, Catalina Sauza), friends from AZIMUT 360 and AIGUASOL, and my soul mates Oriols^2 at H3O.

I want to dedicate this work to

the memory of my grandparents, who bravely withstood the scarcities of post war Barcelona and managed to nurture a bold and peaceful family;

the memory of Prof Abeeku Brew Hammond, for inspiring the vision of a clean energy present and future;

the rural population in Ghana, for their dignity, hospitality and unbeatable optimism;

my Ghanaian and Catalan family, my parents and sisters, for teaching me the how to chase a dream with a backpack full of open-mindedness, and a perfect mix of determination and patience;

and, above all, to my beloved girls, Nana Aba, Ode and Kai; life, with you, is wonderful.

Mi sumɔ nyɛ tamɔ shɛ !!

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ACRONYMS AND ABBREVIATIONS

CAPEX	Capital Expenditure
CCD	UPC Centre for Development Cooperation
CHP/CHCP	Combined Heat and Power / Combined Heat, Cooling and Power
COE/LCOE	Cost of Energy / Levelised Cost of Energy
ECG	Electricity Company of Ghana (public electricity distribution utility)
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency (West Africa)
FAO	Food and Agriculture Organization of the United Nations
FiT	Feed in tariff – Tariff at which electricity is sold when injected into a national (mains) distribution grid
GEF	Global Environment Facility
IRR	Internal Rate of Return
LHV	Lower Heating Value
M&O&M	Management, Operation and Maintenance
NGO	Non-Governmental Organisation
NPV	Net Present Value
OPEX	Operational Expenditure
ORC	Organic Rankine Cycle
PBT	Payback time
PURC	Ghana Public Utilities Regulatory Commission
PV	Photovoltaic
RE	Renewable Energy
SDGs	Sustainable Development Goals
SEforAll	Sustainable Energy for All
UN	United Nations
UNDP	United Nations Development Programme
VRA	Volta River Authority (public electricity generation utility)
WB	The World Bank Group
WHO	World Health Organization

1 INTRODUCTION AND RESEARCH BACKGROUND

1.1 ACCESS TO ELECTRICITY AND SUSTAINABLE DEVELOPMENT

Access to energy is crucial to any activity we can think of; from domestic to community, commercial or productive initiatives, the capacity and ultimate scope of everything we can do as individuals or as a society is conditioned by the quantity and the type of energy we can use. Figure 1 shows primary energy consumption levels per country in 2014 - note that the colour codes refer to consumption per capita, thus giving a first and very clear reference on the current inequalities in energy consumption in the world.

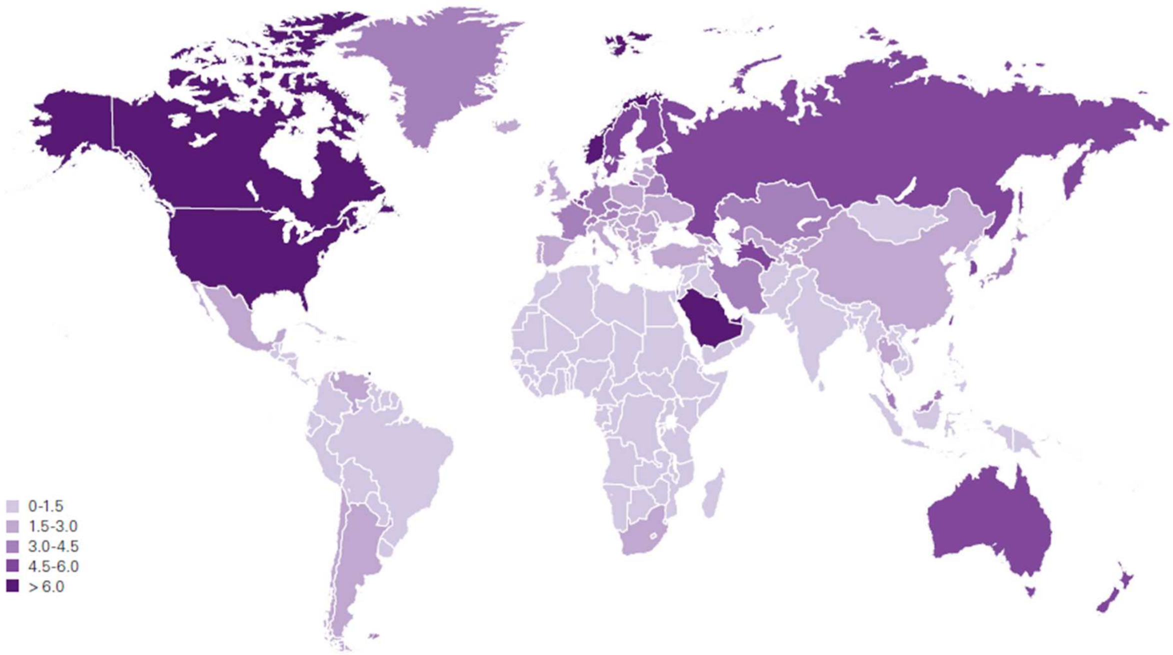

Figure 1. Primary energy consumption per capita (TOE) in 2014. Total world's primary energy consumption: 13.000 Mtoe[1]. (BP, 2015).

We currently depend very heavily on fossil fuels (Oil, Natural Gas, Coal), with very few exceptions in the world today. However, at this stage we are all conscious that our current situation is not sustainable, given the increasing scarcity of fossil fuel reserves, price fluctuations, supply shortages, and the negative effects on global climate. At the same time, there are many areas in the world with little or no access to energy (Figure 1).

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[1] TOE – Tonnes of oil equivalent – unit of Energy. 1 toe is equivalent to 41868 MJ or 11630 kWh

The years to come are indeed a great challenge, in our quest for combining global access to energy and a more sustainable supply of such energy. The World Energy Assessment (UNDP, 2000) defined *"sustainable energy" as energy produced and used in ways that support human development over the long term in all its social, economic and environmental dimensions.* A more specific vision can be found in UPC "Sustainable Development" textbook (Xercavins, 2005), which recommends that *"Regarding energy, policy objectives must be clearly defined, universal access to clean and renewable energies should be set up; there should be political commitment, such as user training programmes; subsidies for fossil fuel utilization should be abandoned; there should be an adequate application of technology to achieve high energy efficiency and improved technologies without fossil fuels."*

The inequalities shown in Figure 1 are clearly noticeable in the specific case of electricity, as indicated in Figure 2.

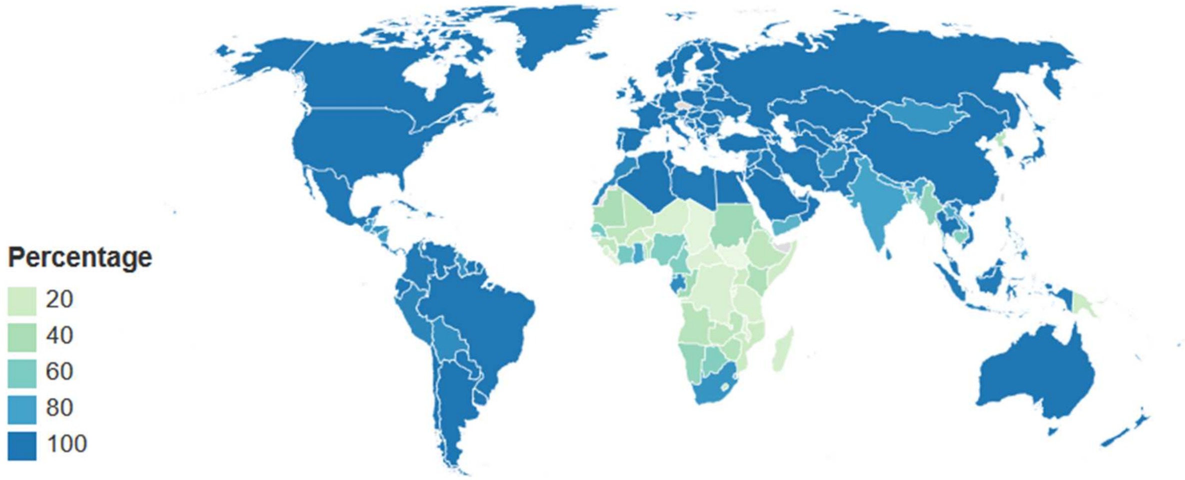

Figure 2. Percentage of population with access to electricity in 2014[2]

Even though the Millennium Development Goals (MDGs) did not have a specific target for energy, it was globally agreed that energy was the one thing that underpins the success of all the goals. The recently formulated Sustainable Development Goals (SDGs) were therefore emphatic on the role of energy for development. One of the targets of Goal 7 is to '*expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, especially least developed countries, small island developing states, and land-locked developing countries, in accordance with their respective programmes of support*' (United Nations, 2016). Per the targets, Goal 7 directly supports the implementation

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[2] http://blogs.worldbank.org/opendata/psd/chart-over-1-billion-people-had-no-access-electricity-2014

of the "Sustainable Energy for All (SEforAll)' agenda launched by the United Nations Secretary General, which has been embraced by many developing countries (Mensah et al., 2014).

Undoubtedly, today's biggest scourge in electricity supply is the enormous number of people who still do not have access to electricity services. The International Energy Agency (IEA) estimates that a population of nearly a billion currently lacks access to such services, while 3 billion people continue to rely on solid fuels (traditional biomass and coal) for cooking and heating, mainly living in rural areas of sub-Saharan Africa and South Asia (IEA, 2017). The main barrier to universal electricity access is therefore supply to rural areas which are not connected to the electricity grid (Alfaro *et al.*, 2016; Azimoh *et al.*, 2016; Eder *et al.*, 2015). The situation in sub-Saharan Africa is poignant: more than half of the population live without electricity or access to modern energy services, in what experts have come to address as the "Hidden Energy Crisis" (Sánchez, 2010). Sub-Saharan Africa has more people living without access to electricity than any other region in the world (Table 1) – 588 million people, and nearly half of the global total. It is also the only region in the world where the number of people living without electricity is increasing, as rapid population growth is outpacing the many positive efforts to provide access. In thirty-seven (37) sub-Saharan countries, the number of people without electricity has increased since 2000 while the regional total rose by around 100 million people (OECD/IEA, 2014). Only a few countries, including Ghana and South Africa, have managed to increase access to electricity to a higher percentage. But even for the few countries with higher access, achieving high rural electrification rates remains a challenge, with a present national average rural access to electricity rate of about 50% (Kemausuor and Ackom, 2016).

Table 1. Electricity access in the world in 2016 – Regional aggregates (IEA, 2017)

Region	Population without electricity (millions)	National electrification rate	Urban electrification rate	Rural electrification rate
Africa	**588**	**52%**	**77%**	**32%**
Sub-Saharan Africa	**588**	**43%**	**71%**	**23%**
Nigeria	**74**	**61%**	**86%**	**34%**
Developing Asia	**439**	**89%**	**97%**	**81%**
India	239	82%	97%	74%
Developing countries	**1.060**	**86%**	**94%**	**70%**
WORLD	**1.060**	**86%**	**96%**	**73%**

An interesting reflection has to do with the relation between electricity consumption and relative welfare; previous studies based on UNDP and IEA statistics have shown that after a certain consumption threshold, there is no significant increase in human welfare (Martínez and Ebenhack, 2008). Figure 3 shows such effect by considering the Human Development Index (HDI) indicator, and the reference consumption per capita is in the range of 4000kWh per year.

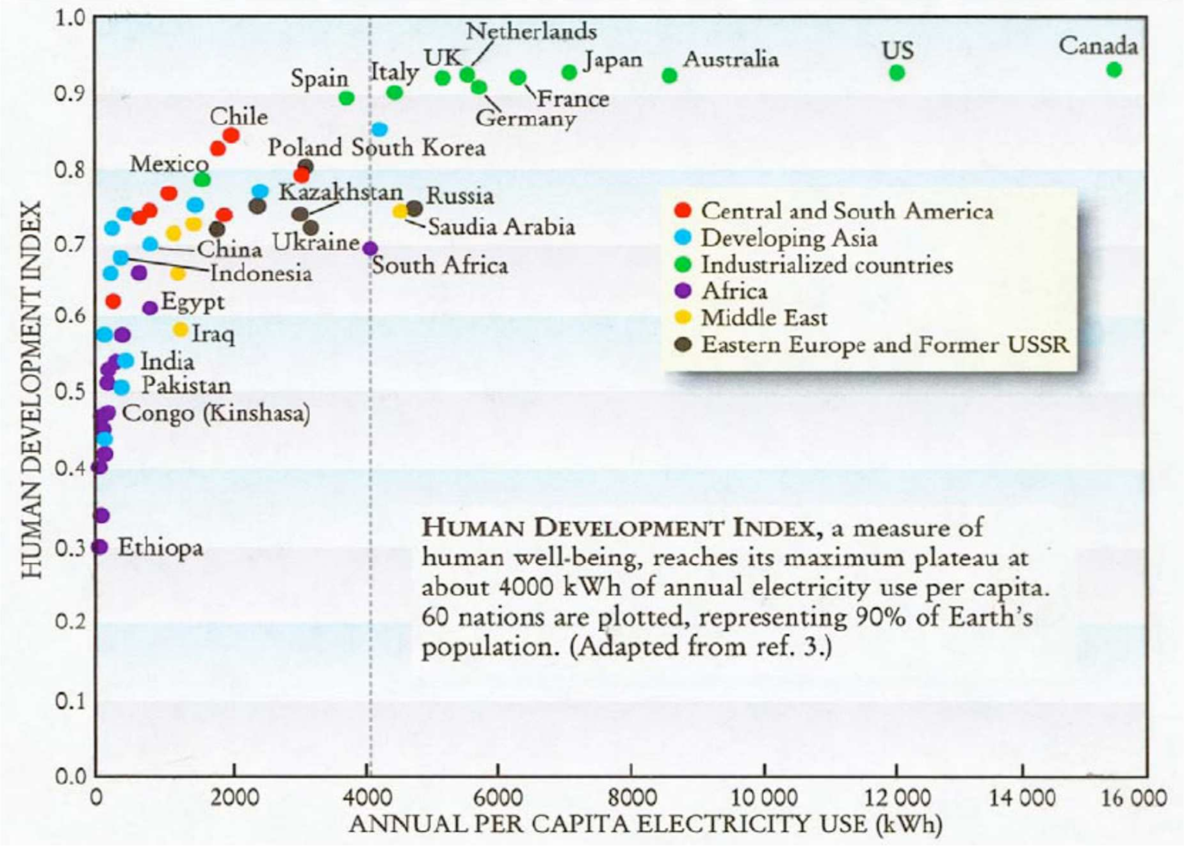

Figure 3. Relation of electricity consumption with human welfare indicators

Following current energy planning trends, based on national centralised infrastructures, it is virtually impossible for the majority of the world's poor to access energy services. Over the last decade, rural electrification programmes based on decentralised (i.e. stand-alone or off-grid) renewable energy systems (mainly solar photovoltaic and micro or pico hydroelectric systems) have proliferated worldwide, as a solution to the lack of access to electricity services in areas far from the conventional grid and an alternative to fossil fuel-based generator sets.

The ultimate goal of any decentralised electrification scheme must be the achievement of a 24-hour homogeneous coverage of electricity service. Previous studies have stressed the lack of integrated approaches in energy planning as a fundamental drawback for a larger success of cleaner and more sustainable energy solutions, based on renewable energy technologies (Silva and Nakata, 2009). Practitioners in the field consider that there are no fundamental technological barriers for a large-scale diffusion of decentralised renewable energy based systems, but mainly lack of long term policy planning and inter-institutional coordination. Over the past decade, UNDP has been stressing three key areas in which capacity building is needed in order to meet the energy access challenges for rural areas, which are still much valid nowadays (UNDP, 2010; IEA, 2017; IEA, 2017b, Borello et al., 2015):

- strengthening national policy and institutional frameworks,
- mobilizing and expanding financing options, and
- developing effective approaches to scale up energy service delivery at the local level.

As a final reflection of this section, energy services are becoming a pivotal concept to characterise the access to sustainable energy planning, allowing an adaptation of the classical three pillars of sustainability - the social, environmental and economic pillars, to a more effective formulation based on the integration of technology, policy and business models (E4tech, 2013).

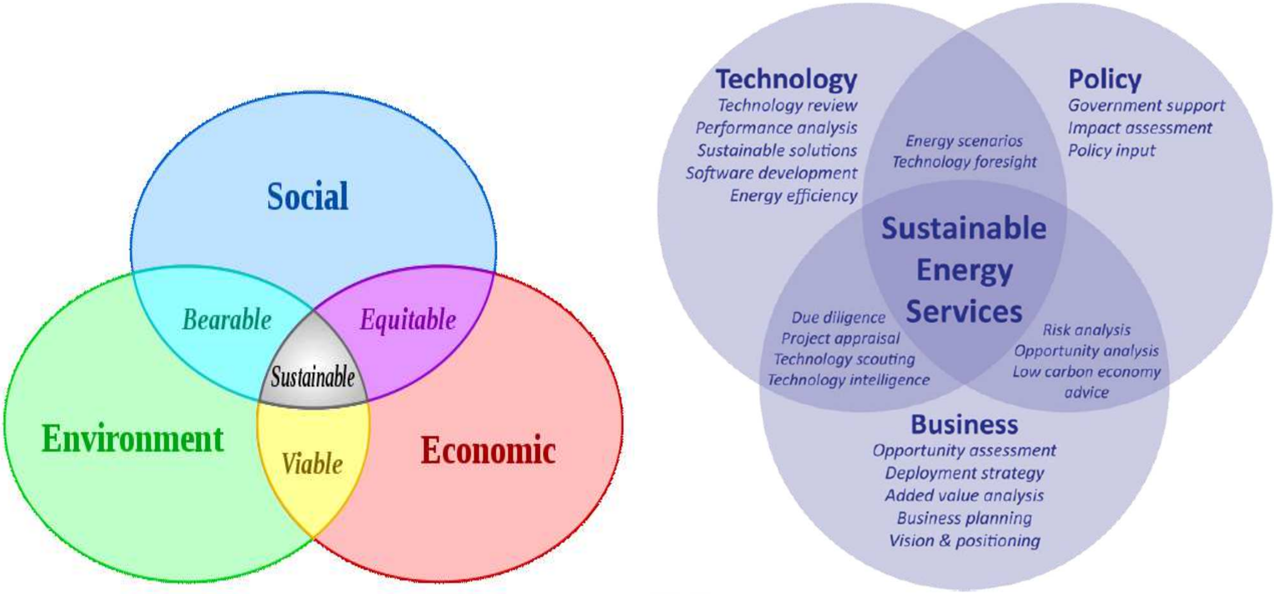

Figure 4. (left) The three pillars of sustainability – general approach. (right) Practitioner approach to sustainable energy services developed by the anglo-swiss private consultancy E4tech (http://www.e4tech.com/)

1.2 THE ELECTRICITY SECTOR IN RURAL GHANA

Ghana is an example of a sub-Saharan African country that has invested in rural electrification systems. This is part of a National Electrification Scheme that has been under implementation since 1990, initially formulated to reach universal access to electricity in the country by 2020, and nowadays being revised to 2030. Ghana has also subscribed to the SEforALL agenda and was the first country to prepare an SEforALL Action Plan (Mensah *et al.*, 2014). Ghana's SEforALL Action Plan aims to continue the drive for rural electrification and promote productive uses of electricity (Government of Ghana, 2012). Currently, about 15% of the population (an estimated 4 million people), living in remote areas and island communities where extending the national grid is difficult and costly, remain without access to electricity (Kemausuor and Ackom, 2016).

A significant portion of this population live in lakeside and island communities on the Volta Lake, which means that grid extension to these communities may require expensive underwater cables. Generally, grid-based electrification to these communities is highly uneconomical (Nerini et al., 2016). According to Sánchez *et al.* (2015), when the costs of transmission lines are too high because of distance, dispersion and maintenance issues, the use of distributed generation is the only possible solution.

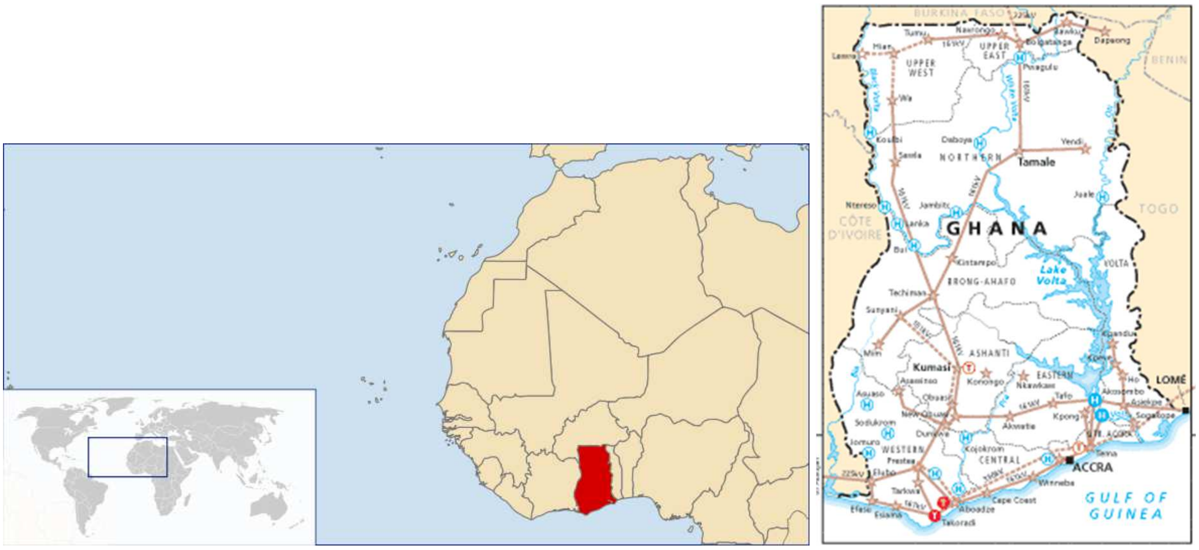

Figure 5. Map of Ghana in West Africa

In view of this, the Government of Ghana is targeting the construction of 55 renewable energy-based mini-grids by 2020 (Government of Ghana, 2015), with an ultimate aim of reaching at least 300 mini-grids by 2030. The targeted locations for mini-grids deployment is expected to be lakeside and island communities, as well as rural off-grid communities (Government of Ghana, 2015). In 2016, five pilot mini-grids were commissioned in island communities, but these are all solar hybrid based technologies, with wind and diesel genset backup (TTA, 2017).

Meanwhile, many of such rural communities produce agricultural residues and other biomass types that could be converted using biomass-based power plants to meet their electricity demands. Biomass electricity systems that use appropriate feedstock and technology, could contribute towards meeting targets on mini-grid electrification in Ghana and other sub-Saharan

African Countries where mini-grid programmes are being promoted. This system of power generation, apart from providing the rural communities with self-sufficient energy (ESMAP, 2016), can also generate employment and other development opportunities for the rural inhabitants, through the productive use programme being targeted by the national SEforALL programme.

1.3 ENERGY FROM AGRICULTURAL RESIDUES IN GHANA

In most Ghanaian rural communities, as in most sub-Saharan African countries, agricultural residue biomass is an abundant resource that can be supplied on a regular basis. According to Sánchez *et al.* (2015), power generation from biomass at the local community could add value to local production schemes based on agriculture. However, existing studies on biomass utilisation in Ghana have targeted resources at the national level (Gyamfi *et al.*, 2015; Mohammed *et al*, 2015; Kemausuor *et al.*, 2014; Duku *et al.*, 2011), regional and district levels (Ayamga *et al.*, 2015; Kemausuor *et al.*, 2014a), agro-industrial level (Asibey *et al.*, 2017; Ramamurthi *et al.*, 2016; Kemausuor *et al.*, 2015; Ramamurthi et al., *2014*), or clusters of agricultural residue to supply biomass to larger scale power plants (Arranz-Piera *et al.*, 2017).

The only community level study that we have sighted modelled biogas production systems for a rural community (Kemausuor *et al.*, 2016). We have not come across any study that looks critically at the entire feasibility chain of using indigenous agricultural residue to supply power to communities using decentralized systems.

Financial viability of biomass systems in Ghana is another issue that has not been given much attention in the scientific literature. Financial viability may be dependent on government energy policies, and what incentives are available for producers (Kerdsuwan and Laohalidanond, 2015; Sampim and Kokkaev, 2014; Dasanayaka, 2012). It has been asserted by Ekinci (2010) that for biomass systems to be economically viable, financial mechanisms must be put into effect, such as increasing market price of electricity produced from biomass plants to give an incentive to producers and offering both long-term credits and tax breaks for investors. If such support systems ensure profitability, biomass plants could encourage private investment (Borello *et al.*, 2015).

Profitability may also be dependent on other factors such as the number of operating hours in the year, which directly affects the amount of electricity produced and fuel consumed, as well as investment expenditures (Borsukiewicz-Gozdur *et al.*, 2015). Indeed, most renewable energy projects face higher capital and technology costs, and cannot financially compete with conventional energy projects. This leads to less interest of private sector if government support is not adequate to reduce the investors' risk. Many of these issues have not been given adequate attention in the case of Ghana. Generally, critical issues such as resource potential, demand typologies, costs, and effect of government support at the community level have not been evaluated.

Policy support to bioenergy in Ghana include:

- The Renewable Energy Act, 2011 (Act 832), which sets a Feed-in-Tariff to guarantee the price of electricity generated from renewable energy resources, such as biomass. The feed-in-tariff rate fixed for electricity from renewable energy sources shall be guaranteed for a period of ten years and subsequently be subject to review every two years.
- Renewable Energy Purchase Obligation, which obliges power distribution utilities and bulk electricity consumers to purchase certain percentage of their energy requirement from electricity generated from renewable energy resources such as biomass. In specifying the percentage level of electricity, the following factors shall be taken into account:
    - the technology being used to generate electricity from renewable energy resources.
    - the net effect of the cost of renewable energy on the end user tariff.
- Renewable Energy Fund, established to provide incentives for research, promotion, development and utilization of renewable energy resources such as biomass. The funding sources of the fund include Moneys approved by Parliament, Premiums, Donors, Levy from biofuel export.

1.4 BIOMASS FOR ELECTRICITY GENERATION

Rising fossil fuel prices and increasing concerns about climate change are creating a growing demand for new sources of raw material for sustainable electricity and heat production (Hoffert *et al.*, 2002; Eisentraut and Brown, 2012; Mertens and Goodwin, 2014). For countries with poor access to electricity and modern fuels, biomass provides an alternative fuel source that can be explored for the production of modern energy to meet rising energy demand and spur socio-economic development (IEA, 2013; Bazmi *et al*, 2015; Kemausuor *et al*, 2015; Cutza *et al*, 2016). Home grown biomass resources offer significant potential for increasing the quantity and controlling the rising costs of raw material to produce energy. Many of these biomass resources are usually underutilized and, in theory, there are considerable opportunities to use them as an energy source (Rosillo-Calle *et al*, 2008; Silva and Nakata, 2012; Ullah *et al*, 2015).

Already, biomass plays a very important role in global energy provision. In 2014, biomass contributed 14% to global final energy consumption (REN21, 2016). The so-called ‘modern biomass’, in the form of heat and power, contributed approximately 5.1%, while traditional biomass contributed 8.9%. Total primary energy supplied from biomass reached approximately

60 EJ (REN21, 2016) and is the main cooking fuel source for about 2.6 billion people in developing countries. It has been predicted that biomass is likely to remain an important global source in developing countries well into the next century (IEA, 2013). Presently however and as presented from the statistics above, the use of biomass has principally been in traditional forms, as charcoal and firewood, with very low efficiencies. The inefficiencies associated with the use of biomass in traditional forms, as well as associated harmful environmental, health and social effects has enhanced the growing interest in the search for better application of biomass globally (Grieshop *et al*, 2011; WHO, 2016).

In the July 2005 Gleneagles Plan of Action, the G8 +5 (Brazil, China, India, Mexico and South Africa) agreed to "... promote the continued development and commercialisation of renewable energy by: [...] d) launching a Global Bioenergy Partnership to support wider, cost effective, biomass and biofuels deployment, particularly in developing countries where biomass use is prevalent"[3]. The foundational purpose of the Global Bioenergy Partnership is to provide a mechanism for its multilateral and governmental partners to organize, coordinate and implement targeted international research, development, demonstration and commercial activities related to production, delivery, conversion and use of biomass for energy, with a focus on developing countries. In December 2011, the GBEP published a set of 24 sustainability indicators for bioenergy (Table 3), categorised under the three general pillars of sustainability.

Electricity supply from biomass is specifically addressed by indicator 14 “Bioenergy used to expand access to modern energy services”, and its current formulation is mainly focused on developing countries. Electricity is also taken into account in indicators 17 “Productivity”, 20 “Change in consumption of fossil fuels and traditional use of biomass”, 23 “Infrastructure and logistics for distribution of bioenergy”. These indicators are seen by GBEP as starting points from which policy-makers and other stakeholders can identify and develop measurements and domestic data sources that are relevant to their nationally defined needs and circumstances. The indicators are currently under a series of validation processes by several countries, including Ghana. In the last GBEP Task Force on Sustainability meeting report (November 2017), the Ghanaian implementation body (Ghana Energy Commission) reported that “increased financial resources are needed for improved data availability and quality”[4].

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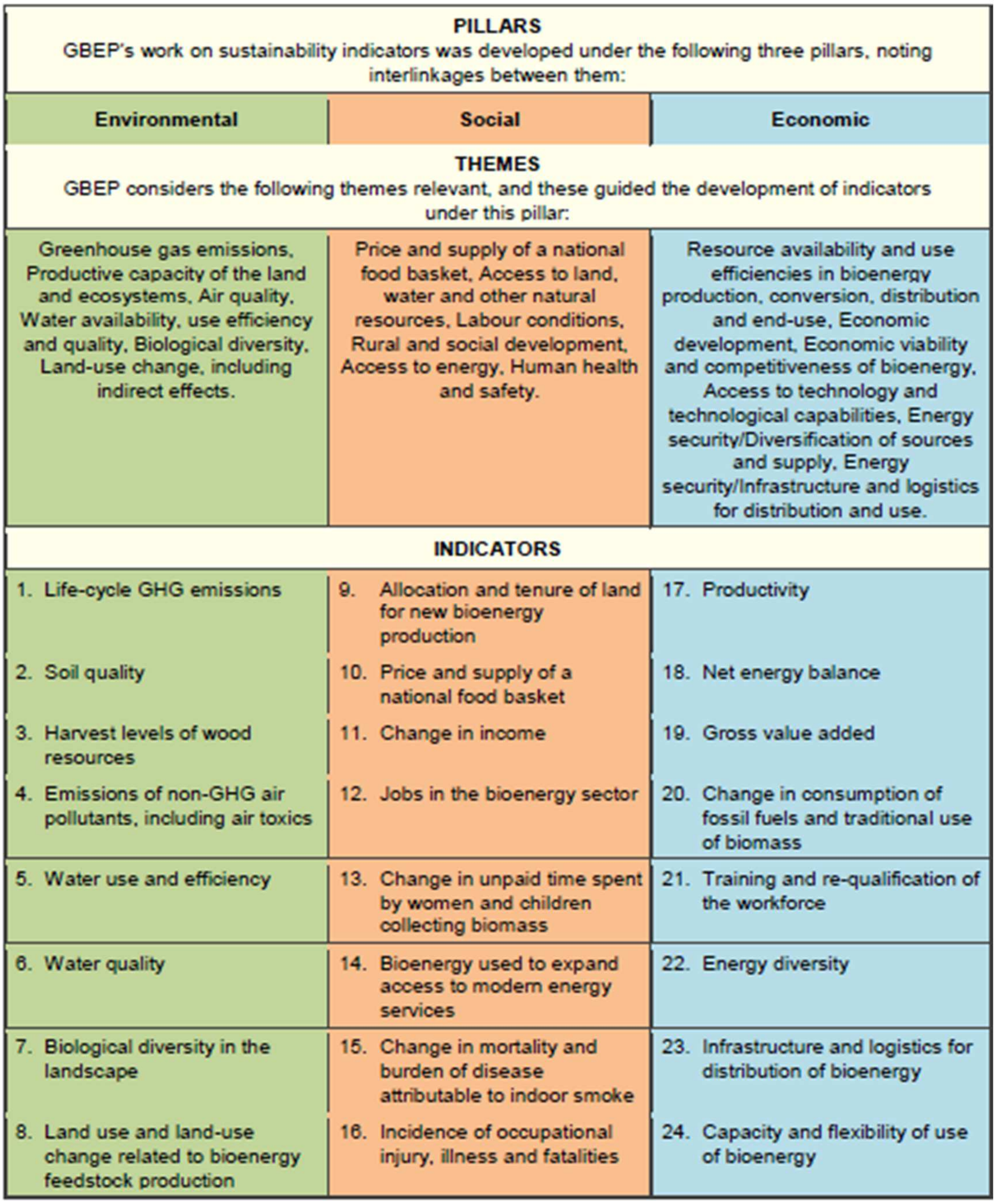
[3] http://www.globalbioenergy.org

[4] http://www.globalbioenergy.org/programmeofwork/task-force-on-sustainability/en/

Table 2. Sustainability indicators proposed by GBEP in December 2011.



PILLARS GBEP's work on sustainability indicators was developed under the following three pillars, noting interlinkages between them:		
Environmental	**Social**	**Economic**
THEMES GBEP considers the following themes relevant, and these guided the development of indicators under this pillar:		
Greenhouse gas emissions, Productive capacity of the land and ecosystems, Air quality, Water availability, use efficiency and quality, Biological diversity, Land-use change, including indirect effects.	Price and supply of a national food basket, Access to land, water and other natural resources, Labour conditions, Rural and social development, Access to energy, Human health and safety.	Resource availability and use efficiencies in bioenergy production, conversion, distribution and end-use, Economic development, Economic viability and competitiveness of bioenergy, Access to technology and technological capabilities, Energy security/Diversification of sources and supply, Energy security/Infrastructure and logistics for distribution and use.
INDICATORS		
1. Life-cycle GHG emissions	9. Allocation and tenure of land for new bioenergy production	17. Productivity
2. Soil quality	10. Price and supply of a national food basket	18. Net energy balance
3. Harvest levels of wood resources	11. Change in income	19. Gross value added
4. Emissions of non-GHG air pollutants, including air toxics	12. Jobs in the bioenergy sector	20. Change in consumption of fossil fuels and traditional use of biomass
5. Water use and efficiency	13. Change in unpaid time spent by women and children collecting biomass	21. Training and re-qualification of the workforce
6. Water quality	14. Bioenergy used to expand access to modern energy services	22. Energy diversity
7. Biological diversity in the landscape	15. Change in mortality and burden of disease attributable to indoor smoke	23. Infrastructure and logistics for distribution of bioenergy
8. Land use and land-use change related to bioenergy feedstock production	16. Incidence of occupational injury, illness and fatalities	24. Capacity and flexibility of use of bioenergy

The Global Network on Energy for Sustainable Development identified several barriers to large scale power generation from biomass in developing countries (GNESD, 2011):

1. Volatility in feed-in tariff. Fixed feed-in tariff policies have spurred interest in the development of co-generation in some countries, such as Brazil and India. However, the lack of a 'fixed' feed-in tariff implies that an investor (for instance in co-generation) has to negotiate with the distribution utility on a case by case basis.

2. Non-enforceable legal and regulatory instruments. Since co-generation investments are long term in nature, it is imperative that the existing and future legal and regulatory instruments are enforceable by a court of law.
3. Lack of technical expertise. The skills gap ranges from a lack of experts to carry out comprehensive and bankable feasibility studies and engineering studies to a lack of the expertise required for the construction, installation, commissioning and maintenance of advanced co-generation equipment such as steam turbines and high-pressure boilers, as well as gasifiers.
4. Unavailable local financing: While nearly all sugar factories bank with local commercial banks and, in some cases, enjoy healthy business ties, unfortunately local commercial banks do not have the experience or technical capacity to conduct the requisite due diligence to finance co-generation plants. Consequently, sugar factories have to seek investment financing from regional and international development financing institutions, which are not as familiar with the operations in the host country's sugar factories, thus complicating the process of raising investment finance for co-generation.
5. Lack of availability of commercial low-scale technology in sub-Saharan Africa (only available in Brazil and India)
6. Lack of support infrastructure in some regions.
7. High investment costs not affordable by poor small rural communities.

The task facing technology developers and policy makers is to move beyond the use of biomass in traditional forms and to introduce technologies that utilize biomass to produce modern fuels such as electricity and heat at both small and large-scale levels (GNESD, 2011). Current research and analysis is therefore geared towards shifting away from the use of biomass in traditional cook stoves and other inefficient conversion systems to its use as raw material for the production of energy carriers using more efficient conversion processes (Gomez *et al*, 2010; Jimenez *et al*, 2012; Shafie *et al*, 2012; Ullah *et al*, 2015). The use of biomass in modern forms can contribute to increasing the share of renewable energy and decrease the reliance on fossil fuels. In addition, the use of biomass in modern forms can have important environmental benefits (Fernandes and Costa, 2010; Khanna *et al*, 2011; Bilgili, 2012; Dhillon and von Wuehlisch, 2013). Biomass is also an indigenous energy source available in most countries and its deployment on a larger scale may help diversify the fuel-supply in many situations, which in turn will lead to a more secure energy supply (Balat, 2005; Shahbaz *et al*, 2016) - even in emergency situations such as international refugee flows (CEDRO, 2016). The supply chain (security of biomass feedstock supply) is a key aspect in the sustainability of biomass-to-energy solutions, and in this sense the biomass sourcing logistics in low density feedstock areas (like the Mediterranean region, or most of rural West African regions) has not enabled the development of large capacity power plants; dispersed biomass feedstocks can, however, enable the biomass supply to smaller scale generation capacities (also called micro generation), typically below 1MW (Mertens and Goodwin, 2014).

In sub-Saharan Africa, the world's least electrified region, there have been a few specific initiatives aimed at the promotion of biomass use. The BEST (Biomass Energy Strategy) initiative by the EU Energy Initiative - Partnership Dialogue Facility and the German Cooperation (GIZ) worked on a guideline to support the development of African strategies to optimise the use of thermal applications of biomass (traditional biomass sector) but did not specifically cover electricity generation from biomass. Since 2011, the Renewable Energy Facility (EREF) from the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) is also supporting small scale biomass systems development in West Africa. The work presented in Chapter 3 has arisen from a study partly funded by an EREF grant.

1.5 SMALL SCALE BIOMASS TO ELECTRICITY GENERATION TECHNOLOGIES

The spectrum of biomass to energy solutions involve a wide range of materials and technologies. The term "solid biomass" typically refers to dry ligno-cellulosic organic matter. For heat and electricity production, the following thermo-chemical conversion technologies are used: combustion, gasification and pyrolysis (Velo, 2011; IEA, 2017b):

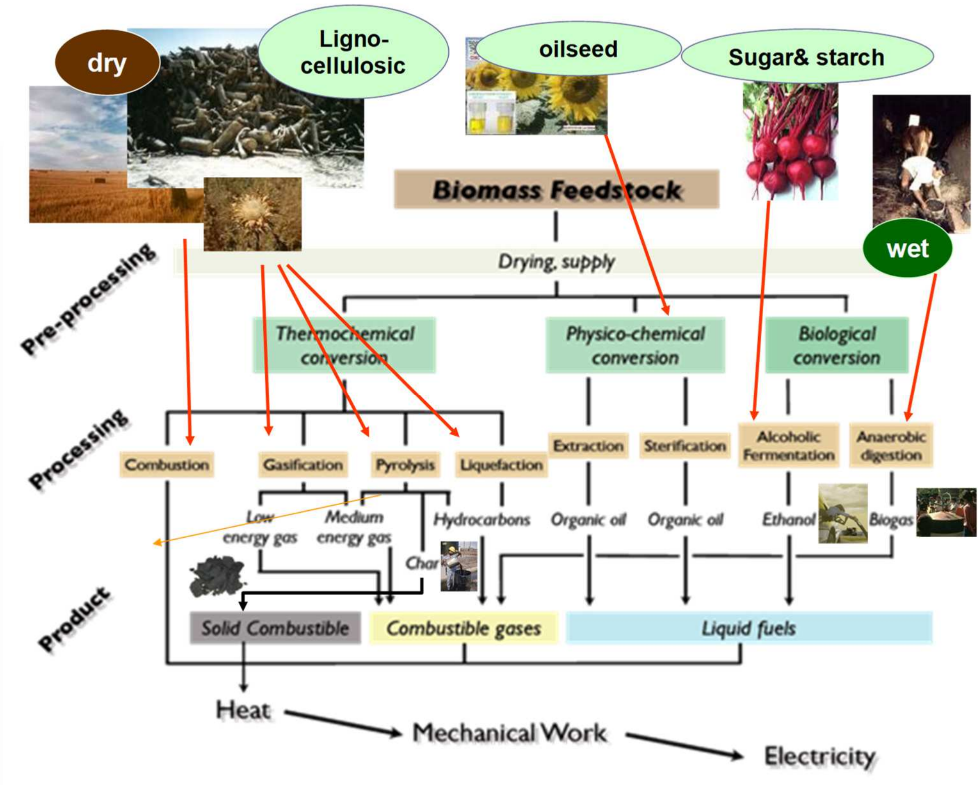


Figure 6. Biomass sources and technologies (Velo, 2011)

Thermo-chemical combustion consists on the complete oxidation of the carbonaceous material, giving hot gases and ashes in the combustor. On the other side, Pyrolysis is the thermal degradation of the carbonaceous material, giving tree main streams: char, liquids, and gases. In the middle of them, gasification is the result of a partial oxidation of the carbonaceous material, giving a fuel gas (producer gas, synthesis gas), as well as ashes. Among them, Pyrolysis is the more flexible process, and an interesting alternative under the biorefinery concept. Nevertheless, when seeking to produce electricity, the more competitive and commercially available processes are combustion and gasification. Conventional approaches of biomass-to-electricity systems range from several megawatts to thousands megawatts, and include well known experiences of sugar-cane mills, and demonstration plants in countries with a high productivity of biomass resources. Depending on the power output capacity required, the most widely used technologies are the Steam Rankine cycle and the Organic Rankine cycle (ORC) (Mertens and Goodwin, 2014). Both technologies are fully mature and readily available; commercial steam Rankine cycles are used in power plants with generation capacities above 2MW, while ORC are used for smaller plants (between 600 kW and 2MW capacities).

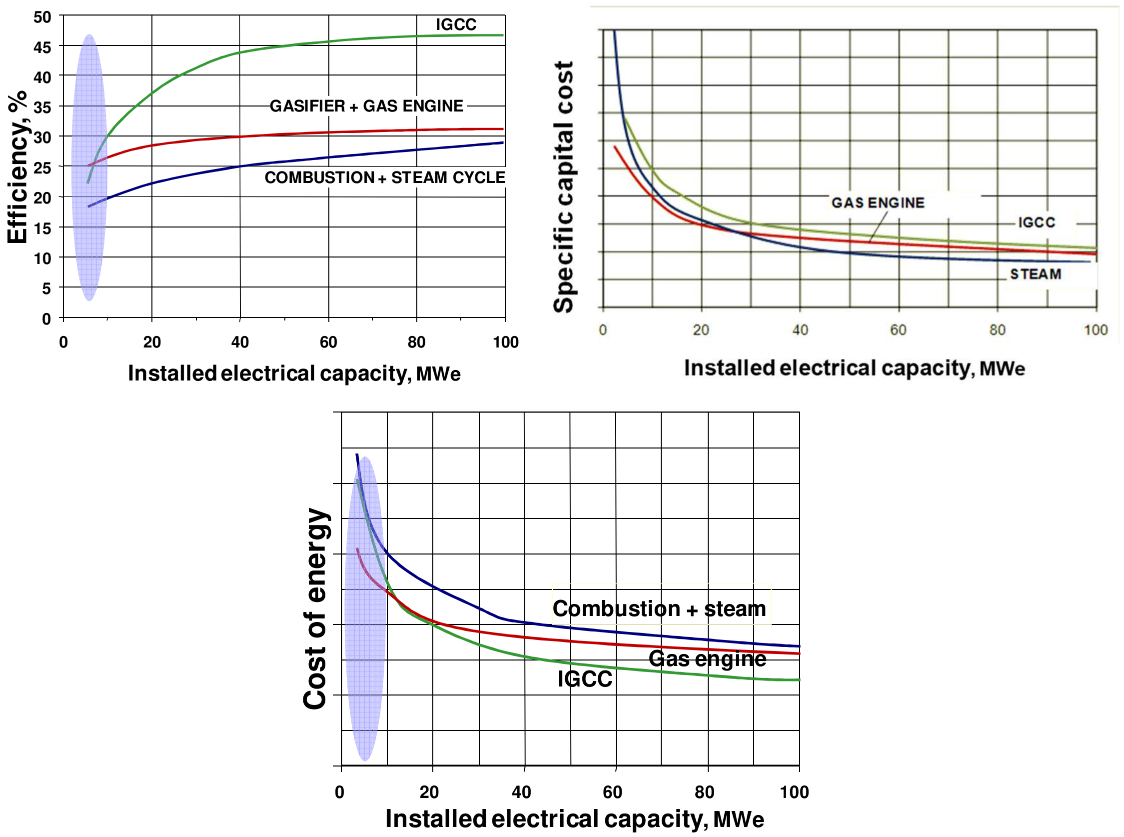


Figure 7. Comparison between biomass-to-electricity technologies (Velo, 2011).

In terms of economics, the main indicator considered when comparing different options for power generation is the levelized cost-of-energy (Vallvé et al., 2007). In a simple approach, this is directly related to the energy efficiency, the capital, and operation and maintenance costs. These parameters strongly depend on the facility size; figure 7 shows that for power plant capacities below 5 MW, a gasifier coupled to a conventional (internal combustion) gas engine has the best figures in efficiency, specific capital cost, and cost of energy. Other studies have identified gasification as the most promising small scale (below 100kW) solid biomass to electricity conversion technology (Mohammed et al., 2015, González et al., 2015). Moreover, an environmental life cycle analysis study of different biomass to electricity options by Siegl et al. (2011) has shown that gasification (using wood chips) has lowest environmental impact of all.

Mar Pérez Fortes, in her PhD Thesis (Pérez-Fortes, 2011) provides a review of the development of small scale biomass gasification. With the first experiences with gasification dating back to the 18th century, low prices of fossil fuels during the 20th century led to a generalised abandoning of biomass gasification, not to be retrieved until the 1990's. Conditioned by the dependence on fossil fuel usage, small scale biomass gasification has been characterised by a discontinuous technology development, changeable public funding support and a pioneering role from research and other non-energy specialist agents such as rural development NGO's or concerned individuals. Hence, even if gasification is not a "new" process, research is still needed due to the low commercial maturity achieved by small scale gasification reactors, thus involving a not extended know-how. The producer gas quality is the key aspect in biomass gasification; its specific requirements will be determined by its final application. Synthesis gas, a.k.a syngas, is a mixture of mainly H_2 and CO, with different proportions of H_2O and CO_2. Usually, the term producer gas is used to describe a syngas with H_2, CO and CH_4, coming from a low temperature gasification. Typically, low temperature gasification counts with air as gasifying agent. Thus, the producer gas normally has an important fraction of N_2. Syngas and/or producer gas is referred to as a medium energy gas, ranging from 4 to 18 MJ/m_3 of calorific value, depending on the gasifying agent (McKendry, 2002).

For capacities smaller than 1 MW, fixed bed reactors are used (vs fluidised bed reactors). S. Chopra and A. Jain provide a review of fixed bed gasifiers schemes (Chopra and Jain, 2007). The fixed bed gasifier can be classified according to the ways in which the gasifying agent enters the gasifier and reacts with the biomass (which follows a top-down path). i.e. updraft, downdraft, crossdraft and two stage gasifier. The updraft gasifier is suitable essentially for thermal applications, using biomass containing high ash (up to 15%) and high moisture content (up to 50%) and generate producer gas having high tar content (50–100 g/Nm^3). Downdraft gasifiers yield producer gas with lower tar content (1-2 g/Nm^3) than updraft gasifiers, thus making them much more appropriate for engine applications such as electricity generation.

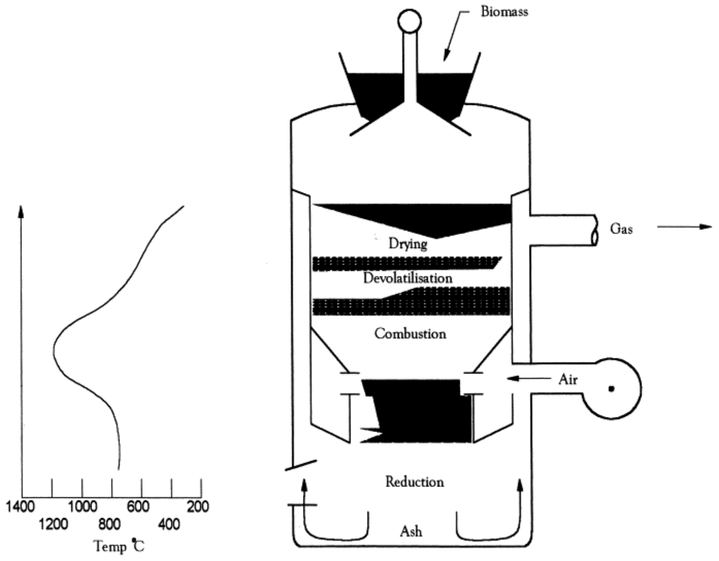


Figure 8. Schema of a downdraft gasifier (McKendry, 2002)

Throated close-top downdraft biomass gasifiers, commonly known as "Imbert" gasifiers, are suitable to handle biomass fuel having ash and moisture content less than five per cent and 20% respectively. Throatless downdraft gasifiers have been developed to overcome the problems of bridging and channelling in Imbert downdraft gasifiers. The throatless gasifiers have been successfully used for gasification of rice husk, wood chips, bagasse, sugarcane leaves, coconut shells etc. Additionally, a biomass gasifier can be combined with other renewable technologies in a hybrid system concept (Figure 9).

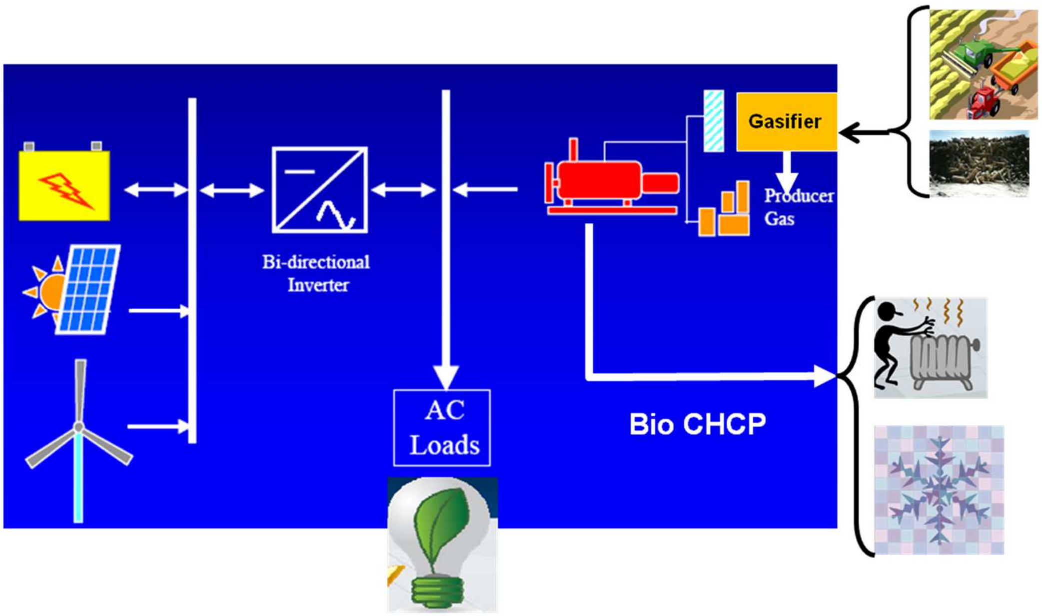


Figure 9. Schema of a hybrid renewable energy system integrating a solid biomass gasifier with other renewable energy sources (Escorcia et al., 2012)

2 AIMS AND METHODS

2.1 OVERALL OBJECTIVE

The overall objective of this work has been to develop a planning methodology for sustainable decentralised electricity generation schemes based on solid biomass residues, and to apply it in rural areas of Ghana.

2.2 SPECIFIC OBJECTIVES

- Characterise the social, institutional, technical and financial metrics of small scale electricity generation facilities based on solid biomass.
- Elaborate a framework for the feasibility analysis of decentralised power generation from biomass, addressed to decision-makers, electrification projects' developers and managers, and electricity service operator entities.
- Test and validate this framework under **three representative configurations in Ghana**: (i) decentralised power to grid generation, (ii) tri-generation, and (iii) off-grid minigrid services in rural communities.

2.3 METHODS

2.3.1 Planning framework development

Based on the findings of the research background presented in section 1, the planning components of small-scale electricity generation from biomass have been studied, with a focus on characterising their key aspects and respective metrics. The next step has been to combine and integrate such components in a qualitative framework to enable the analysis of electrification programmes or projects from a sustainability point of view.

2.3.2 Application to configurations

To test the planning framework, 3 real case biomass-to-power configurations in Ghana have been assessed by applying the framework components and quantifying their metrics, in order to obtain and discuss planning feasibility results.

For each configuration a specific literature review and case study methodology have also been conducted. The results and conclusions obtained have been discussed both with the practitioner and the academic community, and have resulted in 3 peer-reviewed paper publications (Energy and Energy Procedia journals, Elsevier editorial group).

2.3.3 Primary field data collection

This research has put special effort in collecting primary data for each of the configurations assessed. Up to 15 rural districts from 6 different regions in Ghana have been visited to survey smallholder farms, irrigated rice farms and off-grid communities, including more than 250 interviews to local stakeholders – farmers, households, community leaders, administration officers (District Assemblies, Ministry of Energy, Ministry of Food and Agriculture, Energy Commission, Public Utilities Regulatory Commission), rural banking institutions, as well as field offices of the electricity distribution utilities: the Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCo).

Figure 10: Field work visits to rural communities and rice farms in the Brong-Ahafo region.

Further details on the sites visited and information retrieved are provided in the specific methodology sections of each Biomass-to-Electricity configuration investigated in this research, presented in the following sections.

3 INTEGRATED PLANNING FRAMEWORK

Sections 1.1 and 1.2 have pointed out the specificities of energy demand assessments in developing countries. Lessons learned from experiences in the field (Vallvé et al., 2007; Tenenbaum et al. 2014) have shown some key factors conditioning demand that need to be carefully addressed in rural electrification:

- Population nuclei, dispersed and located in remote areas, lack road and communication infrastructures, as well as provision of basic services (sanitation, health, education)
- Users have low energy and power demands
- The majority of the population, poorer than in urban areas, have a very low liquidity and lack access to financial mechanisms
- Users generally have a low educational level and lack access to information.

Another approach used in assessing renewable energy systems penetration (Arranz-Piera et al., 2003) is the contemporary model of diffusion of innovations first developed by E.M Rogers in 1962 and since then revisited periodically by the same author, among others (Rogers, 1995). Diffusion is defined as "as the process by which an innovation is communicated through certain channels over time among the members of a social system". Hence, four main elements are identified: the innovation itself, the communication channels, time and the social system. Implementation of small-scale electricity generation systems using solid biomass (an object of the proposed Thesis) can be indeed considered as an innovation, both in industrialised areas and developing countries. An interpretation of the social system (in the diffusion of innovations model) underlying an energy access intervention can be based in the three basic units:

1. **Communities**: Target population or users of a planned electricity service. Their socio-economic benefit must be the final goal of the action.
2. **Programme (or Plan)**: Integral action scheme comprising design, implementation, monitoring and evaluation in the mid and long term. Sets the regulatory, institutional, social development and financial components of the planned action. The duration of a programme is variable (depending on the desired impact), typically ranging from 3 to 15 years.
3. **Project**: Sequence of specific actions for the materialisation of the directives set in a programme in the short term. Based on the selected communities, sets the technological, economic and organizational component of the planned action. The duration of a project is variable (depending on the available resources), typically ranging from 1 to 4 years. One same project can be aimed at more than one community, and one same community can be addressed by more than one project.

Most importantly: an electrification project must allow the start-up of an energy service and lay the grounds for its sustainability (Arranz-Piera et al., 2011). The following key components can be considered within programmes and projects in an integral approach to energy services:

Table 3. Key components underlying any sustainable electrification project or programme

Programme	**Project**	*Goal (as an energy service)*
Social Development	Social Integration	*Equity*
Institutional	Organisational	*Empowerment*
Technical	Technological	*Reliability*
Economic	Financial	*Viability*

Considering the above key components conceptualisation, many examples of interesting academic exercises but with little short and midterm practical applicability by electricity planners and investors can be found in the literature. For instance, the works of Felipe Henao et al (2012) exploring the technique of Sustainable Livelihoods pentagon in Colombia, or Mar Pérez Fortes et al (2012) developing a multi-objective Mixed Integer Linear Programming algorithm and applying it to a case study in Ghana. Still, research in this line can contribute to refine the optimisation techniques in electricity planning.

The framework for off-grid rural electricity service provision analysis developed in this research is summarised in Figure 11.

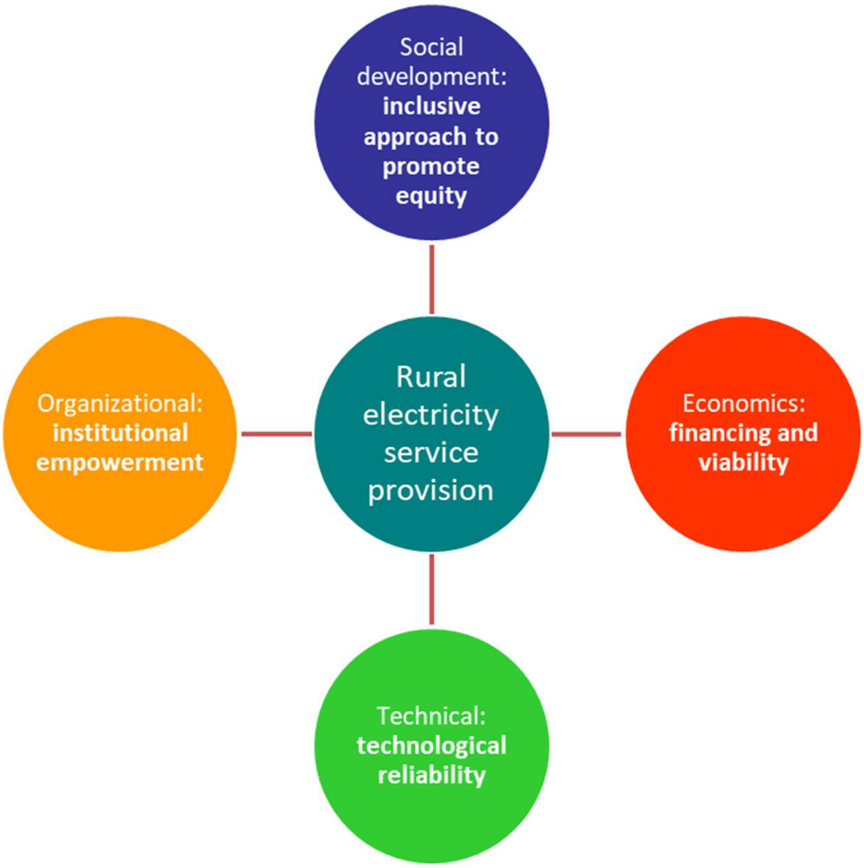


Figure 11: Key components of the planning analysis framework applied in this research

The framework is based on an iterative approach, emphasizing the necessity of starting by determining a need or an interest for the energy service and how residents desire to use the service. Once interest/desire has been established and the level of consumer involvement has been assessed, the technical details can be designed. These are finetuned per the results from the preceding steps, leading to the choice of an appropriate technology. Before implementing a technology, the intersection of the project and the roles (and effective capacities) of various related actors should be considered. Depending on the delivery mechanism (public development, private development, public-private partnership, community based, etc.), the stakeholders may include administrative bodies, private companies, NGOs, community groups, and multilateral international agencies. Finally, the financial details of setting up the project are assessed. The cost and pricing of the technology are determined and the project is evaluated per economic metrics such as the Payback (PBT), Net Present Value (NPV) and Internal Rate of Return (IRR).

3.1 SOCIAL DEVELOPMENT COMPONENT

The ultimate aims of a rural electrification programme or project is the improvement in livelihoods of the rural population. An inclusive approach covering as many socio- economic aspects of the targeted population as possible is therefore essential, both in the cases of energy access driven interventions (where universal access and equity are the social goals, typically the case of public sector developments) and productive uses of energy facilitation (where full range power service supply made available to customers is the goal, typically the case of private sector initiatives) (Tenenbaum *et al.*, 2014; RECP 2014, ESMAP, 2017).

The key issues under this component are preliminary energy demand assessment of the target communities. This includes not only households, but energy demand for productive and commercial activities. As rural communities grow, essential services such as public lighting, schools and clinics expand, or new ones are built, and this must be considered when planning long term electrification projects. To have community acceptance of energy projects, socio-cultural structures and the recognition and effective comprehension of an advantage in the energy service to be introduced have been recognised as critical in previous works based on the sociological theory of innovation diffusion developed by Rogers (Rogers 1995; Miller, 2010; Eder *et al.*, 2015). Existing uses of biomass resources or the intended resource for electricity generation, as well as existing organisational structures, literacy levels and community values must be factored into the overall planning framework. Most rural communities have great respect for community leaders, especially chiefs and spiritual custodians. The ability to win over such leaders is a necessary step to project success.

3.2 ORGANIZATIONAL AND INSTITUTIONAL COMPONENT

This component involves the inclusion of energy access policy and administrative powers at the national, regional and local levels. Following the lead of the key components described in Table 3 and considering the stakeholder mapping needs derived from the five forces competitive strategy model described previously, this framework pays attention to the exhaustive identification of the agents that participate in an electrification action. Building on the analysis of several experiences and international standards on small decentralized energy infrastructure[5], Table 4 presents an identification of key roles for an efficient inter-institutional framework, based on the differentiation of responsibilities to be applied to any electricity sector or socio-political context. The electricity service operator models (or business models) are defined with input from these administrative units, factoring in existing community experiences and existing regulations. Following the definition of the applicable service operator model is the determination of biomass supply chains, or other resources thereof.

Table 4: Roles and responsibilities of main actors in the framework[6]

Key Roles	**Main Responsibilities**
Programme or Project Developer	Planning, control and management of the programme over its whole life. Ensure communication with and between the key roles.
Institutional developer	Defines objectives, strategies and mechanisms for the project execution, per the conditions set by the regulator. In a top-down, public sector led action, typically the institutional developer will act as project developer.
Regulators	Establishes the conditions for the biomass sourcing, infrastructure implementation and management of the service (licensing, permitting, tariffs, quality criteria, subsidies, etc.).
Standardising agent	Establishes the technical conditions for the infrastructure implementation and management of the electricity service (equipment certification and guarantee, quality criteria, safety).
Funder(s)	Provides economic resources.
Users	Beneficiaries from the service; must commit to the system conservation, and to the payment of a tariff for the service.
Social developer	Represent and assist the users' rights, mediate and communicate with other key roles. In a bottom-up action, typically the social developer will act as project developer (e.g. NGO led projects, such as European Commission Energy Facility examples[7])
Technical director or Implementer	Controls the adequate execution of the infrastructure execution and the service start-up. Can provide further assistance to the service operator or the users, if required.
Generators	Own the generation systems assets and produce electricity under the quality conditions set by the Regulator and Standardising agent. In a private sector led action, typically the generator or the service operator (below) will act as project developer.

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[5] Technical Standard IEC 62257-6 "Recommendations for small renewable energy and hybrid systems for rural electrification – Part 3: Project development and management – Part 6: Acceptance, operation, maintenance and replacement". November 2005.

[6] A single organization can play several key roles, and one specific key role can be fulfilled by several organizations.

[7] http://energyfacilitymonitoring.eu/

Key Roles	Main Responsibilities
Electricity service operator	Controls the sustained and correct operation of the system, the service financing and users' payments.
Installer(s)	Adequate installation, start-up and commissioning of the system equipment.
Maintenance provider	Technical specialist conducts maintenance of the system infrastructure (spare parts, collection of used parts, etc.).
Biomass supplier(s)	Production and supply of the biomass resource, under the conditions and quality criteria set by the Regulator and Standardising agent.
Infrastructure provider(s)	Supply materials and equipment (and corresponding guarantees).
Trainer – communicator	Conducts specific training and capacity building activities for local technicians, users, and other local entities involved in the management of the system.
Evaluator or Inspector	Periodical supervision of the infrastructure execution and service provision per the conditions set by the regulator. Verifies the adequacy of the global performance in accordance to the objectives, strategies and mechanisms set by the project developer.
Dissemination director	Conducts promotional and awareness raising activities regarding the infrastructure implemented and the service provided.

3.3 TECHNICAL COMPONENT

Reliability is the goal of this component. Grid-equivalent quality standards are applicable for decentralized electricity service based on biomass. A decentralized (or stand-alone) electricity system must generate reliable energy supply of sufficient quality (generation subsystem), manage and provide energy generated to each point of consumption (distribution subsystem) and provide energy service to users (demand subsystem). The functions of a distributed generation system are summarized in Figure 12.

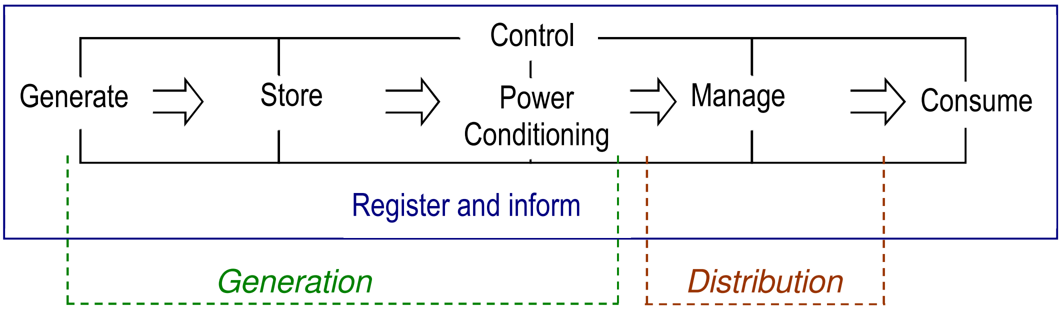


Figure 12: Main functions of stand-alone supply of electric power (Arranz-Piera, 2006).

Before any specificities of each RE technology, the main feature of an electricity supply system must be to guarantee a certain level of quality to meet the user's energy demand (Egido and Camino, 2008) and to be reliable. Compared to diesel generators, RE solutions offer higher modularity and flexibility to adapt to variable load regimes (e.g. over a day profile or due to seasonal ties). The first technical limitations have to do with the availability of natural energy resource, which can eventually be resolved with hybrid systems. In the case of biomass-based systems, certification and standards for sustainable feedstocks sourcing must be developed, focusing primarily on domestic agro-forestry residue and supply chains covering the whole biomass to electricity chain.

Quality assurance has been recognized as a key factor to drive improved sustainability, greater market confidence, and expanded investment in decentralized infrastructure (NREL, 2016). Regardless of the delivery mechanism or business plan followed, quality must be ensured throughout the entire supply chains – components technical specifications, price quotations, contracting, inspection, service start-up, provisional acceptance, warranty period, final acceptance, availability of spare parts, post-sale service. The lack of formal documentation of any of these stages should be a reason for non-agreement or non-compliance.

After the start-up of the energy service, it is necessary to consider three maintenance levels: Basic (often realized by trained users); Professional Preventive (e.g. annual or semi-annual reviews), and Professional Corrective (in the event of incidents or breakdowns).

3.4 FINANCIAL COMPONENT

In the financial component, the appraisal of financial viability requires a long term, holistic approach, and the typical analytical framework widely used both in academia and real project development is life cycle planning (and accounting). A life cycle approach is used to analyse the costs incurred during the design, supply, construction, start-up and management/operation/maintenance (M&O&M), during the operational life of the project (IFC-ERC, 2015).

Based on the typical functions of a mini-grid as presented in the previous section, and after the review of available documentation on mini-grids, the following set of capital expenditure (CAPEX) categories have been considered:

i. Generation;
ii. Storage & powerhouse;
iii. Conversion;
iv. Distribution;
v. Services (project development, engineering, training); and,
vi. Logistics

Based on decentralised power generation literature (Tenenbaum *et al.*, 2014), operational expenditures (OPEX) are split between fixed (staff, dissemination and monitoring, evaluation and inspection, permitting) and variable (current electricity consumption from the grid – in the grid connected case studies -, boiler or gasifier filter cleaning or substitution, engine gas generator maintenance, and, eventually, biomass residue supplies).

Revenues will mainly accrue from the sale of electricity, either to (i) the grid or to (ii) final consumers in the off-grid configurations. In the first case, feed-in tariffs will be assessed. In the second case, an important aspect of the financial component will be the willingness to pay and ability to pay levels of beneficiaries, which shall explore current expenditure that could be replaced by the electricity service. Awareness creation may be necessary here for households to understand the dynamics of paying for electricity services. From this point of view, the consideration of costs per average customer (monthly tariff to be paid) is relevant and useful when assessing the affordability of electricity services from mini-grids (Arranz-Piera *et al.*, 2006; ESMAP, 2017).

Depending on the situation and incentive schemes available, subsidies and taxes should be factored into the financial analysis.

Profitability indicators such as Payback Period (PBT), Net Present Value (NPV) and Internal rate of Return (IRR) should then be calculated to conclude on the financial viability of a proposed intervention.

3.5 SUMMARY TABLE OF THE INTEGRATED PLANNING FRAMEWORK

Table 5: Proposed framework for rural electrification project or programme planning analysis

Component	Social development	Organizational/Institutional	Technical	Economic/Financial
Key issues	- Location and preliminary demand assessment of the targeted rural communities. - Prioritisation of services to cover household, commercial, communal and productive purposes. - Income generating activities (existing and potential) and study of the formal and informal biomass energy markets. - Socio-cultural structures of the communities – organization, literacy levels, socio-cultural values, biomass role within local culture. - Local capacities, political and administrative leadership intra and inter communities. - Definition of programme duration and milestones. - Selection of indicators for monitoring and evaluation, setting up of a weighted qualitative indicators matrix for project scoring and qualification. Use of local biomass sources can be a ranking criterion, as well as fossil fuel genset substitution by biomass systems.	- Energy access policy and administrative powers at the national, regional and local levels. - Definition of electricity service operator models (grid connection, off-grid vendor/concession/fee-for-service, community, mixed) according to current regulations. - Current biomass supply chains, identification of main actors involved. - Definition of the key roles that should take part in the intervention, and appointment of the ones without whom the intervention should not progress (by legal enforcement, direct appointment of tender processes). - Definition of administrative criteria for electrification Project qualification within the Programme, as well as related evaluation processes.	- Definition of electricity service quality performance criteria – typically, grid-quality standards also applicable for decentralized biomass generation. - Technical conditions for concession regimes (typically, minimum power generation capacity level above which it is compulsory to apply for a concession). - Pre-selection of technological solutions that will qualify within the programme. Use of biomass-based systems can be a ranking criterion, as well as fossil fuel genset substitution. - Development of certification and standards for sustainable biomass sourcing (focusing primarily on domestic agro forestry residue) and supply chains covering the whole biomass to electricity chain. - Determination of biomass feedstocks availability and thermo-chemical conditions - Definition of technical criteria for electrification Project qualification within the Programme, as well as related evaluation processes.	- Definition of minimum levels of profitability. - Quantification of social benefits of the biomass sourcing and electricity service. - Users willingness to pay (WTP) and capacity to pay (CTP) levels (assessment of the current expenditure that could be replaced by the electricity service). - Appraisal and Design Costs (of the social, technological and economic aspects). - Capital (Infrastructure) and O&M costs. - Availability of subsidy schemes (donations, cross-subsidies, taxes) and/or micro credits schemes, and type of costs that these schemes can be applied to. - Tariff schemes applicable - Availability of private investment (national or international) or multilateral financing.

4 FIRST CONFIGURATION – DECENTRALISED BIOMASS POWER GENERATION FROM CLUSTERED SMALLHOLDER AND IRRIGATION FARMS

4.1 ABSTRACT

In farming communities in Ghana and the West African region, crop residues are often unused and remain available for valorisation. This study has analysed the prospects of electricity generation using crop residues from smallholder farms within defined clusters. Data was collected from 14 administrative districts in Ghana, where surveys were conducted, and residue-to-product ratios determined in farmer fields. Thermochemical characterisation of residues was performed in the laboratory. The number of clustered farms, reference residue yields, and residue densities were determined to assess the distances within which it would be feasible to supply feedstock to CHP plants. The findings show that in most districts, a minimum of 22 to 54 larger (10 ha) farms would need to be clustered to enable an economically viable biomass supply to a 1000 kWe plant. A 600 kWe plant would require 13 to 30 farms. Financial analysis for a 1000 kWe CHP plant case indicate that such investment would not be viable under the current renewable feed-in-tariff rates in Ghana; increased tariff by 25% or subsidies from a minimum 30% of investment cost are needed to ensure viability using internal rate of return as an indicator. Carbon finance options are also discussed.

This section is based on the publication:

Pol Arranz-Piera, Francis Kemausuor, Ahmad Addo, Enrique Velo, Electricity generation prospects from clustered smallholder and irrigated rice farms in Ghana, ***Energy***, Volume 121, 15 February 2017, Pages 246-255.

4.2 LITERATURE REVIEW

The successes of any new form of biomass energy will most probably depend upon the use of advanced technology at a reasonable cost. Among the important drawbacks of modern bioenergy is the complexity of the supply chain (from biomass sourcing to energy consumption) and the economic costs associated with the conversion of the resource. For this reason, the integration of biomass in the energy planning of a community / country requires the development of advanced planning and economic tools that allow for assessing and optimizing costs in order to identify the optimal location for biomass investments (Fernandes and Costa, 2010, De Meyer *et al*, 2016). Indeed, if bioenergy is to have a long-term future, it must be able to provide affordable, clean and efficient energy forms. A number of studies have been conducted into the potential of biomass to provide modern fuels (see for example Rodriguez *et al*, 2011; Ruiz *et al*, 2013; Liu *et al*, 2014; Borsukiewicz-Gozdur, 2014; Nguyen *et al*, 2014; Maung and McCarl, 2013; Ullah *et al*, 2015).

Like many other developing countries, biomass is a dominant energy source in Ghana (Kemausuor *et al*, 2014). In 2014, traditional biomass contributed 39% to primary energy supply. In rural communities, a little below 90% of households use woodfuel as their main cooking fuel. Because of the agrarian nature of Ghana's rural economy, there are opportunities to use biomass resources for the production of modern fuels such as biogas, to complement traditional biomass use in rural communities (Brew-Hammond *et al.*, 2008). In urban communities, residues from oil palm mills and timber processing, as well as waste from fruit processing and crop residue, offer interesting possibilities for the production of electricity and heat for internal applications and also for export into the grid. One of the aims of Ghana's Renewable Energy Act (RE Act), which was enacted by parliament in 2011, is to promote the utilisation of biomass for the generation of electricity and heat.

In line with this, a number of scientific studies have been conducted which indicate a high potential for modern biomass fuels in Ghana. Notable studies include those by Duku *et al* (2011), Mohammed *et al* (2013) and Kemausuor *et al* (2014). However, these studies have focused on aggregated feedstocks at the national level.

There is limited study on potentials of feedstock at the community level, where crop residues could be used in small and medium scale technologies for distributed generation. The aim of this study was therefore to analyse small farm typologies and irrigated rice farms in selected districts in Ghana to determine prospects of using crop residues within defined clusters to generate electricity, with a high replication potential across the country.

4.3 METHODOLOGY

4.3.1 Crop residue assessment methodology

The first stage in the analysis of biomass for electricity generation is the assessment of biomass resource availability. The resource assessment is important as it goes hand-in-hand with technical feasibility study and provides the baseline for financial pre-feasibility studies. For this study, the prospects of using crop residues from small-scale aggregated farms and irrigated large rice farms were investigated in a fieldwork that principally considered types of crops cultivated, farm sizes, and potential residue yield from fourteen (14) districts in Ghana. A summary of the methodology is presented in Figure 13. The districts were selected to reflect the different agro-ecological zones in the country, from the forest zone, through the transitional zone, to the savannah zone.

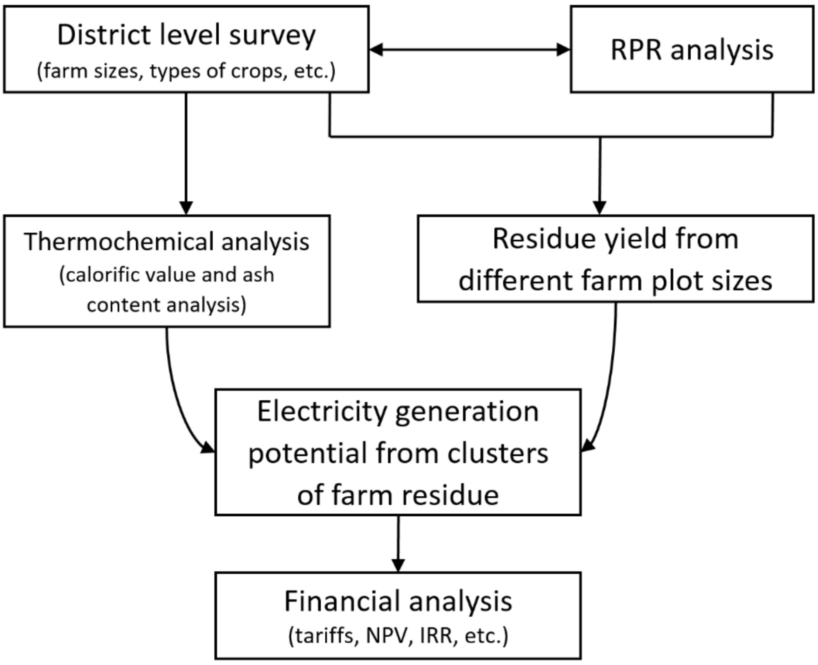


Figure 13: Summary of methodology (Configuration 1)

The selection was also based on districts that have relatively high crop production figures within each agro-ecological zone, based on earlier studies by Kemausuor *et al* (2013). Crop residue available was estimated using the Residue-to-Product Ratio (RPR). Fieldwork to determine RPR was conducted in twenty-two (22) farming communities from the selected districts in Table 6. Maize is cultivated in all the selected districts and is also the commonest crop cultivated in the country by area.

Every district in the country cultivates maize as one of the main crops. Cassava was the next most common crop, cultivated in the forest and transition agro-ecological zones in the country. Other crops, including yam, sorghum and millet are the least common, restricted to the savannah zone. In all, ten (10) farms were randomly selected from each farming community, bringing the total number of farms to two hundred and eighty (280). RPR was determined using methods described by Ayamga *et al* (2015) and Kemausuor *et al* (2016).

Data on major crops, farm sizes as well as crop yields in the selected districts were obtained from the district offices of the Ministry of Food and Agriculture. Data on medium and large-scale irrigated rice fields was also obtained from the Ghana Irrigation

Development Authority (GIDA) in order to assess husks and straw from larger scale farms (See Table 7).

Table 6: Districts where small/medium holder farms were visited

District	Agro-ecological zone	Main crops
Ejisu Juaben	Deciduous forest	maize, rice, cassava
Asante Akyem north	Deciduous forest	maize, rice, cassava, cocoa
Sunyani west	Guinea Savanna	maize, yam and cassava
Nzema East municipal	Rainforest	maize and coconut
Ejura Sekyedumasi	Transitional zone	maize
Lawra district	Guinea Savanna	millet, sorghum, maize and groundnut
Ga East Municipality	Coastal Savannah	maize and cassava
Nkoranza	Transitional zone	maize and cassava
Techiman	Transitional zone	maize and cassava
Kintampo North	Guinea Savana	maize and cassava
Dormaa	Transitional zone	maize and cassava
Sekyere West	Deciduous forest	maize and cassava
Kintampo south	Transitional zone	maize and cassava
Wenchi	Transitional zone	maize and cassava

The RPR obtained from the field experiments in the various districts, as well as the production amounts and yield per ha of the crops under consideration were used to determine the various residue potentials for 1 ha, 5 ha and 10 ha small holder farms.

Equation 1 was used to determine the amount of crop residues available.

$$P_{AR} = \sum_{i=1}^{n}(C_i \times RPR_i) \tag{1}$$

where, P_{AR} is the annual crop residue potential, C_i is the annual production of crop *i* and RPR_i is the residue to product ratio of crop *i*. Factor *n* is the total number of residue categories.

Table 7: Major irrigated rice production sites in Ghana

Irrigation scheme	Area (hectares)	Rice production (tonnes/year)
Kpong irrigation	1,896	9,482
Tono	1,050	5,250
Afife/Whetta	870	4,350
Bolgatanga	310	1,550
Aveyime	53	268
Okyereko	50	250
Anum valleys	50	250
Colinga	40	200

4.3.2 Thermochemical characteristics of crop residues

Thermochemical characteristics of crop residues were determined based on laboratory experiments and complimented with data from Duku *et al.* (2011) and Brew-Hammond *et al.* (2008). Of the residues considered in this study, thermochemical characteristics were determined in the laboratory for corn stover, corn husks, corn cob, rice husk and millet stalk. Fresh samples of these residue types were collected during the fieldwork and Lower Heating Value (LHV) and ash content determined in the laboratory. The methods used were ISO 1928 for LHV, using a bomb calorimeter and ISO 1171 for ash content, using a Nabertherm L-240H1SN muffle furnace.

4.3.3 Approach to electricity generation feasibility

4.3.3.1 Technologies

Biomass-to-electricity technology systems are already in use in power plants in several countries and industries, notable among which are the sugar-cane milling and timber processing industries (GNESD, 2011). Capacities of these plants range from a few megawatts to hundreds of megawatts. Depending on the power output capacity required, the most widely used technologies are the Steam Rankine cycle and the Organic Rankine cycle (ORC) (Mertens and Goodwin, 2014). Both technologies are fully mature and readily available; commercial steam Rankine cycles are used in power plants with generation capacities above 2 MW, while ORC are used for smaller plants (between 600 kW and 2MW capacities).

A third technology, fluidized bed gasification, has also been developed for the use of biomass residue, and there are a few Combined Heat and Power (CHP) plants in the capacity range of 1 to 10 MW in operation (Mertens and Goodwin, 2014). The main advantage of gasification is a slightly higher electrical generation efficiency (up to 25%-28%), but synthesis gas cleaning, purification and waste management requirements are complex and currently there are very few full commercial suppliers on the market offering this technology with the same level of reliability as ORC plants in the range of capacities considered. Tables 8 and 9 show the technology and the technical assumptions considered in the feasibility analysis discussed in this paper.

Table 8: Energy Conversion Technology considered

Type of Residue	*Electrical Power (MW)*	*Technology considered*
Biomass with high ash contents and/or low density and/or high Alkali content (typically herbaceous biomass and straw – covering all biomass types considered in this study)	600 kW < P < 2 MW	Organic Rankine Cycle (ORC) with biomass boiler

Table 9: Assumptions used for analysis of electricity generation plants*

Boiler efficiency	85%
ORC cycle electric efficiency	18.5%
Minimum hours of operation per year	7,500 hours
Conservative estimation of LHV	Considering 30% MC (on dry basis) of biomass received at the plant

* Based on information from commercial plants developed by one of the most reputed ORC CHP technology developer in Europe, TURBODEN from Italy

4.3.4 Financial viability

4.3.4.1 Financial appraisal methodology used

The main purpose of the financial analysis is to use the project cash flow forecasts to calculate suitable net return indicators. Two financial indicators were considered for the financial analysis:

- the Net Present Value (NPV); and
- the Internal Rate of Return (IRR).

The Net Present Value of a project is the sum of the discounted net flows of a project. The NPV is a very concise performance indicator of an investment project: it represents the present amount of the net benefits flow generated by the investment expressed in one single value with the same unit of measurement used in the accounting tables.

The Net Present Value of a project is defined as shown in Equation 2.

$$NPV = \sum_{t=0}^{n} a_{t}S_{t} = \frac{S_0}{(1+i)^0} + \frac{S_1}{(1+i)^1} + \cdots + \frac{S_n}{(1+i)^n} \qquad (2)$$

where S_t is the balance of cash flow at time *t* and a_t is the financial discount factor chosen for discounting at time *t.*

NPV is a very simple and precise performance indicator. A positive NPV, NPV>0, means that the project generates a net benefit and is generally desirable in financial terms. When comparing projects in financial terms, one with higher NPV is preferred.

The Internal Rate of Return (IRR) is defined as the discount rate that zeroes out the net present value of flows of costs and benefits of an investment as shown in Equation 3. The Internal Rate of Return is an indicator of the relative efficiency of an investment.

$$NPV = \sum \frac{S_t}{(1+IRR)^t} = 0 \qquad (3)$$

The methodology used for the determination of the financial return is the Discounted Cash Flow (DCF) approach with the following assumption: only cash inflows and outflows are considered (depreciation, reserves and other accounting items which do not correspond to actual flows are disregarded).

4.3.4.2 Base scenario financial assumptions

In the base scenario, the composition of the capital required for the implementation of a project is distributed as follows: 70% debt; 30% own funding; 0% subsidy.

Key assumptions forming the basis for major financial/economic inputs to the financial analysis for the feasibility study are described below:

- The plant would be available for operation for 7,500 hours in a year thus giving a capacity factor of 85 percent.
- Cash flows are discounted over a period of 20 years at a rate of 10% to 12% (Pueyo, 2016; Kemausuor, 2015, Ofori-Boateng 2013).
- Loan Repayment is over a period of ten (10) years, at an interest rate of 4.5% (international rates in EUR)
- The plant will enjoy a 100% exemption from income tax payment for the first 5 years of operation based on incentives for 'rural' development projects provided by the Ghana Investment Promotion Council.
- Straight-line depreciation method is assumed for the lifetime of the project.

4.3.5 Project Revenues

The feed-in-tariff (FiT) in Ghana is the regulated price that electricity distribution utility companies would pay to renewable energy generators. The Ghana Public Utilities Regulatory Commission (PURC) published the first FiT in August 2013 and updated same in October 2014 (see Table 10) in line with requirements of the Renewable Energy Act. As at the latest announcement, FiTs in Ghana are valid for 10 years but there are indications of an incoming 20-year FiT in the next review, following industry request.

At the time of performing this analysis, the 20-year FiT is not published yet, hence the analysis used the latest 10-year FiT shown in Table 10. The 2014 FiTs introduced maximum capacity limits for technologies with high variability (i.e. solar and wind) due to the limited capacity of the transmissions and distributions systems to manage highly variable loads. Limits were not imposed on biomass and hydro plants. Biomass FiTs vary between US dollar cents 17.5 to 19.8, depending on the technology type and feedstock source. This study assumes that 100% of the electricity generated from the plants (after internal consumption) is exported and sold to the grid (either the national grid or a dedicated mini-grid), under the reference FiT adopted in Ghana.

Table 10: FiTs published by the PURC

Electricity generated from Renewable Energy Technologies/Sources	**FiT (GHp/kWh) Effective October 01, 2014**	**US cents / kWh equivalent**	**Maximum Capacity (MW)***
Wind with grid stability systems	55.7369	17.4254	300 MW
Wind without grid stability systems	51.4334	16.0800	
Solar PV with grid stability/storage systems	64.4109	20.1372	150 MW
Solar PV without grid stability/storage systems	58.3629	18.2464	
Hydro (≤10 MW)	53.6223	16.7643	No Limit
Hydro (10 MW>≤100 MW)	53.8884	16.8475	No Limit
Biomass	56.0075	17.5100	No Limit
Biomass (Enhanced Technology)	59.0330	18.4559	No Limit
Biomass (Plantation as Feed Stock)	63.2891	19.7865	No Limit

* Maximum capacity was introduced in 2014. Exchange rates: 1US$ = GHC 3.1986

4.3.6 Sensitivity analysis

A basic sensitivity analysis was conducted to assess the impact of an eventual change of the revenues and expenses in the project's expected return. Sensitivity analysis allows the determination of the 'critical' variables or parameters of the model. Such variables are those whose variations, positive or negative, have the greatest impact on a project's financial performance. The analysis is carried out by varying one variable at a time and determining the effect of that change on IRR. By adjusting these variables, it is possible to more confidently project real potential return of the power plant. The critical factors in this analysis are the selling price for electricity, the capital costs, the possibility to benefit from subsidies and/or carbon finance, and the eventual supply cost of the biomass (agricultural residue). The sensitivity was done as follows:

- FiT range from 180 to 350 US$ per MWh
- Eventual biomass (agricultural residue) cost of 5 and 10 US$ per tonne.
- Level of subsidy to initial investment, from 10% to 70%
- Carbon credits at 10 and 130 US$ per tonne CO_2 equivalent.

4.4 RESULTS AND DISCUSSION

4.4.1 Heating value analysis

The results from the LHV and ash content analysis is presented in Table 11. LHV ranged from a minimum 13,000 kJ/kg for rice husk to a maximum of 19,300 kJ/kg for corn stover. The ash content was the exact reverse, starting with a minimum of 1.17% for corn cobs, to 24.47% for rice husk. While we have not sighted any publication that reports LHV for these resources based on experimented results performed on Ghana specific residue, the LHV obtained for corn and millet residues are notably higher than international data reported in Duku et al (2011) and Brew-Hammond et al (2008). On the other hand, LHV obtained for rice husk is lower than data reported in those same publications. An article by Thomsen et al (2014) on experimental results from residues collected in Ghana only analysed ethanol and biomethane potentials of the residues, relying on Buswell's formula to estimate the products from the anaerobic breakdown of a generic organic material. For samples that were not analysed in the laboratory, the LHV and ash content were obtained from Duku et al (2011) and Brew-Hammond *et al* (2008). These included cassava peels, yam straw, coconut shells and sorghum stalks.

Table 11: LHV and ash content obtained from laboratory analysis

Residue type	**LHV (kJ/kg)**	**Ash content (%)**
Corn stover	17,706 ± 24	4.97 ± 0.14
Corn husk	17,221 ± 22	2.70 ± 0.27
Corn cob	19,322 ± 19	1.17 ± 0.01
Groundnut shell	17,432 ± 22	7.05 ± 0.27
Rice husk	13,035 ± 13	24.47 ± 0.40
Millet stalk	17,765 ± 25	2.44 ± 0.07
Cocoa husk*	15,480	11
Sorghum stalks*	17,000	3.9
Yam Straw*	10,610	16.1
Cassava peels*	13,380	4.8
Coconut shells*	18,000	4

* Duku *et al* (2011); Brew-Hammond *et al* (2008).

4.4.2 Residue generation potential in small holder farms

From the survey conducted and data obtained from the respective district offices of the Ministry of Food and Agriculture, smallholder farms in the various districts have been categorized into 3 land areas: small (approximately 1 ha), medium (approximately 5 ha) and large (approximately 10 ha). Large commercial scale farms of tens and hundreds of hectares were not considered in this analysis. Using the residue type generated, the respective RPR, and yield per hectare obtained in each of the districts, the specific yields for each farm category have been determined as shown in Table 12. For example, in the Ejisu-Juaben District, one-hectare sized farms each of maize, rice and cassava will produce approximately 37 tonnes of residue per year. Medium and large farms (five-hectare and ten-hectare) of those same crops would produce approximately 183 and 366 tonnes of residue per year respectively. Of the fourteen districts, the Nzema East Municipality, the only district in the rainforest agro-ecological zone, had the highest residue yields.

Generally, the forest regions had higher residues, compared to the transitional and savanna zones. Also, residue generation from coconut and cassava is much higher on a per hectare basis, compared to the other crops. Based on the estimated residue yields, the residue density was computed as shown in the last column of Table 12.

Table 12: Expected yield from clustered small holder farms

District	**Region**	**Main crops**	**Small holder farms categories reference residue yields** (tonnes/year)			**Residue density** (kg/km^2 day)
			Small 1ha	**Medium 5ha**	**Large 10ha**	
Ejisu Juaben	Ashanti	maize, rice, cassava	37	183	367	10,041
Asante Akyem north	Ashanti	maize, rice, cassava, cocoa	50	250	499	13,677
Sunyani west	Brong-Ahafo	maize, yam, cassava	23	113	227	6,214
Nzema East	Western region	maize and coconut	54	268	56	14,674
Ejura Sekyedumasi	Ashanti	maize	4	19	38	1,027
Lawra district	Northern region	millet, sorghum, maize, groundnut	24	119	239	6,534
Ga East	Greater Accra	maize, cassava	24	118	237	6,488
Nkoranza	Brong-Ahafo	maize, cassava	34	167	333	9,134
Techiman	Brong-Ahafo	maize, cassava	33	165	329	9,025
Kintampo North	Brong-Ahafo	maize, cassava	27	137	273	7,490
Dormaa	Brong-Ahafo	maize, cassava	27	136	273	7,490
Sekyere West	Ashanti	maize, cassava	32	162	324	8,871
Kintampo south	Brong-Ahafo	maize, cassava	34.	170	341	9,332
Wenchi	Brong-Ahafo	maize, cassava	30	150	299	8,195

Having determined the residue yields, the minimum yields needed to feed CHP plants are summarized in Table 13. For rice husks for example, a 1000 kWe plant generating 7500 MWh/year of electricity will require approximately 36 tonnes/day of residue. This has been computed for various capacities of plants, from 600 kWe to 2000 kWe.

Table 13: Example of reference minimum yields for CHP plants using specified residue type

Residue type	Minimum CHP plant Power output (kWe)	Annual Electricity generation at 7500 hours/year (MWh/year)	Annual residue required at 15.72% electrical efficiency* (t/year)	Daily average residue needed (t/day)
RICE RESIDUE	600	4,500	7,896	22
	1,000	7,500	13,160	36
	2,000	15,000	26,320	72
COCOA HUSK	600	4,500	6,666	18
	1,000	7,500	11,109	30
	2,000	15,000	22,219	61
MAIZE RESIDUE	600	4,500	6,514	18
	1,000	7,500	10,857	30
	2,000	15,000	21,714	59

*Based on data obtained from the laboratory

Determination of minimum yields resulted in the computation of the minimum number of clustered small holder farms needed to consider for various capacities of potential CHP plants with details shown in Table 14. Using the set of assumptions described in Table 9, the minimum input biomass availability (in tonnes per day) has been calculated for each size of CHP plant. Below 200 kWe, the technical reliability of CHP plants is not completely mature. Gasification combined with internal combustion engines is commonly regarded as the most promising conversion technology given its higher efficiency than ORC, but to date it is not a fully commercial technology. The use of gasification would in any case need a preliminary phase of in-country (pilot) validation, preferably at a laboratory scale.

Table 14 shows that in the majority of districts, a minimum of 33 to 53 large (10 ha) farms would need to be clustered to enable a viable supply to a 1000 kWe CHP plant. A 600 kWe plant would require 13 to 30 farms. With regards to medium or small farms, the minimum number of clustered farms would be much higher. Two districts: Nzema East and Asante Akyem north, have slightly better conditions than the rest, needing a minimum of 22 large (10 ha.) farms to enable a 1000 kWe CHP plant.

Table 14: Number of small holder clustered farms needed for various plant sizes

District	Min no. of farms for a 600 kWe plant			Min no. of farms for a 1000 kWe plant			Ideal Radius of cluster (km)	
	1ha	5ha	10ha	1ha	5ha	10ha	600kWe plant	1000 kWe plant
Ejisu Juaben	196	39	20	326	65	33	0.8	1.0
Asante Akyem north	144	29	14	239	48	24	0.7	0.9
Sunyani west	316	63	32	527	105	53	1.0	1.3
Nzema East municipal	134	27	13	223	45	22	0.7	0.8
Ejura-Sekyedumasi	1911	382	191	3185	637	318	2.5	3.2
Lawra district	300	60	30	501	100	50	1.0	1.3
Ga East Municipality	303	61	30	504	101	50	1.0	1.3
Nkoranza	215	43	21	358	72	36	0.8	1.1
Techiman	218	44	22	363	73	36	0.8	1.1
Kintampo North	262	52	26	437	87	44	0.9	1.2
Dormaa	262	53	26	437	88	44	0.9	1.2
Sekyere West	221	44	22	369	74	37	0.8	1.1
Kintampo south	210	42	21	351	70	35	0.8	1.1
Wenchi	240	48	24	399	80	40	0.9	1.1

These requirements are rather restrictive, given the rather dispersed nature of smallholder farms. Using a formula proposed by Velo et al (2011) (see details in Figure 14), the radius of dispersion of the small holder farms is also indicated.

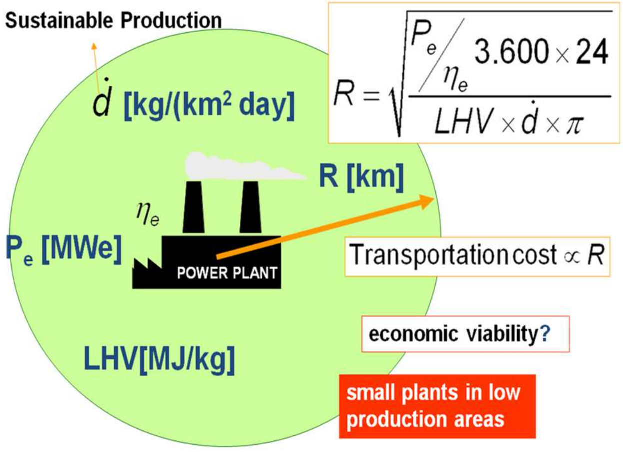


Figure 14: Biomass feedstock production surface area requirement as a function of power plant size (Velo et al, 2011)

For the case of 1000 kWe CHP plant in Nzema East or Asante Akyem north, it can be noted that the required minimum 22 farms should be clustered in an area of about 800m radius from the location of the CHP plant. Within these radius references, and considering a reference of local biomass transport costs of GHC 65 for a load of 2 tonnes at distance of 7 km, transport costs would stay between 17,000 to 18,000 US$ per year.

For further distances, the cost of biomass would increase and seriously challenge the profitability of a CHP plant. The supply logistics will be specific to each case and the residue collection points should be optimized in terms of the location of the small farms, and the CHP plant siting needs to be optimized in terms of collection points and point of feeding into the grid. Therefore, based on the identification of those districts with better prospects carried out in this study, a site-specific basic engineering outline will be needed to define the technical and logistic conditions in detail for each eventual CHP plant development, to finally ascertain the technical viability. Once the technical viability is clear, then specific business models can be considered and adapted to the case of the small holder farms, the security of supply, the specific land ownership regimes, and the potential interest of public or private investors in CHP plant development.

4.4.3 Financial analysis

4.4.3.1 Base case financial results

Summary results of a 1000 kWe plant are presented in Table 15 as a case study. Experience has shown that larger scale plants often have better unit cost, hence the decision to choose the larger of the two plants from the technical analysis for financial analysis. The investment cost considered (from consultations with industrial CHP system suppliers) is approximately US$ 6.5 million or US$ 6,500 per kWe installed. Construction will take place in year 'zero' and the plant is assumed to serve a lifetime of 20 years. Electricity sales would amount to about US$ 1.4 million a year.

The base scenario's NPV over the 20-year project lifetime of the project is US$ -2,775,579 with an IRR of about 4.3% using the latest biomass FiT of US$ 197.87 per MWh approved by the Public Utility Regulatory Commission in November 2014. The NPV and IRR obtained shows that at the prevailing FiT, this is not a viable project for a private business and would require some form of support to make it viable. Under these circumstances, there could be two main approaches: (i) Approve specific (higher) FiT that commensurate with efforts to solve rural electricity challenges; and/or (ii) Consider a certain subsidy on initial CAPEX, to attract private investment.

In addition, biomass from clustered farms could eventually be priced, at least to cover its collection and transport costs (from the farms to the CHP plant). In the sensitivity analysis, the effect of increasing FiT and government subsidy on the IRR at certain costs of biomass are explored.

A third option would be to consider additional income from the use of the residual heat generated at the CHP plants. Such option would imply the development of an agro processing activity with a heating (or cooling) demand in the vicinity of the small holder farms or irrigation projects, which falls out of the scope of this paper.

Table 15: Summary results for base scenario of a 1000 kWe ORC plant

Operating conditions	**Value**	**Unit**
Gross active electric power	1,000.00	kW
Captive gross power	54.00	kW
Gross electric efficiency	20.60	%
Net electric efficiency	19.48	%
Net active electric power	946.00	kW
Operating hours	7,500	h/year
Net electricity production	7,095	MWh/year
Captive gross power	405	MWh/year
Biomass average LHV (30% MC on dry basis)	4	kWh/kg
Biomass demand (30% MC on dry basis)	12,000	Tonnes/year
Thermal energy (hot water 60ºC) available	3,796	kW
Thermal energy (hot water 60ºC) available	28,470	MWh/year
Investment, O&M and biomass costs		
Investment industrial rate	6,497	US$ / kWe installed
Estimated investment cost	6,497,350	US$
Staff cost	75,000	US$/year
Maintenance cost	97,460	US$
Total O&M	172,460	US$
O&M cost / net MWh generated:	24.31	US$/MWh
Biomass cost*	0	US$ / Tonne
Taxes	0	US$
Annual review of O&M prices	5	%
Electricity and thermal energy prices		
Feed in Tariff – (reference - November 2014)	197.87	US$ / MWh
Annual review of FiT	0	%
Thermal energy price	0	US$/MWh
NPV (after 20-year financial period)	-2,773,843	US$
IRR (20-year financial period)	4.3	%

*Biomass cost of 'zero' is typical of irrigated rice projects where rice husks are generated at the processing plant and a CHP plant could also be sited therein, eliminating the need for transport. In the sensitivity analysis, biomass is costed over a certain range, to cover transportation cost for smallholder farms.

4.4.3.2 Sensitivity analysis

The base case operating assumptions makes the project unviable for investment. The effects of increasing the FiT, access to subsidies to initial investment and carbon finance is explored in the following sections.

Increase of Feed-in-tariff (FiT)

Figure 15 shows the sensitivity of profitability (IRR at 20 years, 12% discount rate) versus increases in the FiT, under three different biomass cost references: no cost, 5 US$/tonne and 10 US$/tonne. It can be noted that the pricing of biomass would clearly demand for higher FiT to be allocated to such investment to reach minimum profitability thresholds. To achieve a 12% IRR after 20 years, FiT would need to be increased to 250 US$/MWh (or 25 US$cents/kWh), about 25% increase on the current FiT rates.

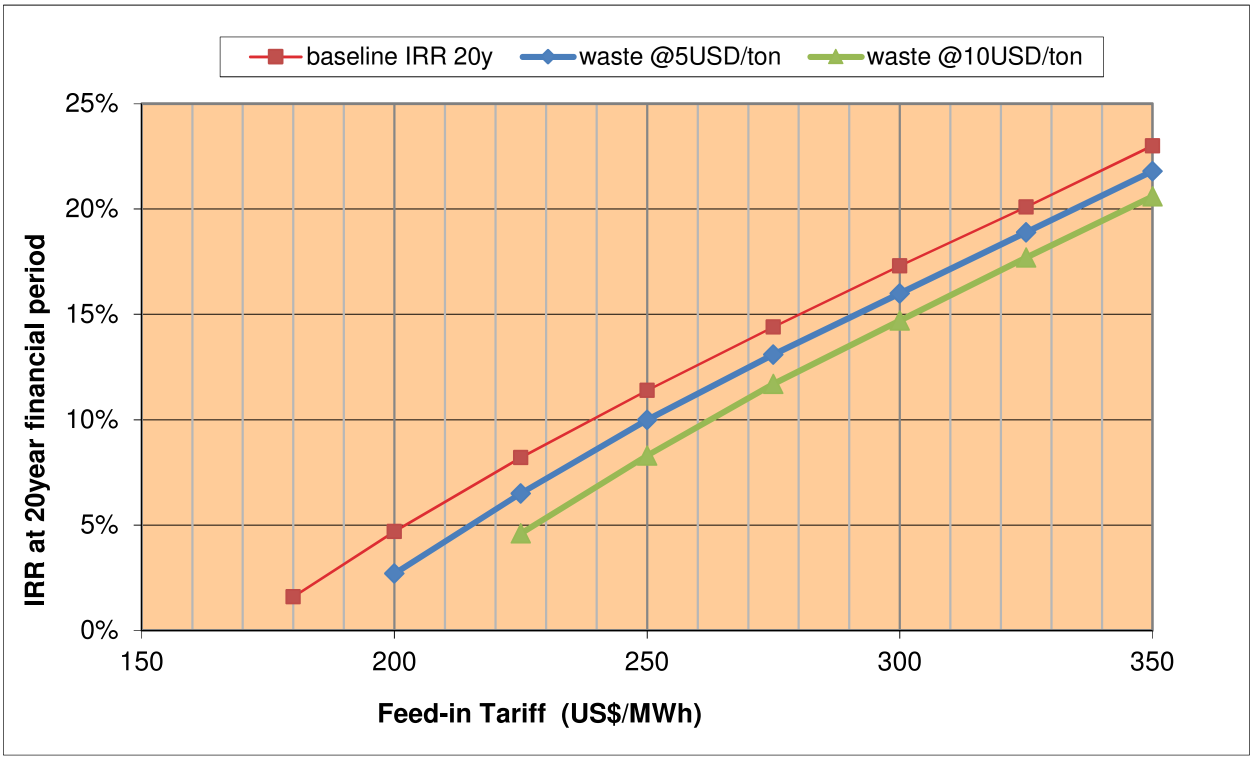


Figure 15: IRR sensitivity to feed-in- tariff rates

Access to subsidies to initial investment

Figure 16 shows subsidies on initial investment under the current FiT rates. Here again, the sensitivity of profitability versus subsidy on initial investment is explored under three different biomass residue cost references: no cost, 5 US$/tonne and 10 US$/tonne. It can be noted that under the current FiT rates for biomass, a minimum of 30% subsidy on the

CHP plant investment cost would be needed to enable a financial profitability of 12% IRR on a 20-year financial period analysis. A higher subsidy, between 35% and 45% would be needed to achieve similar IRR if the biomass residue cost ranges between 5 to 10 US$/tonne.

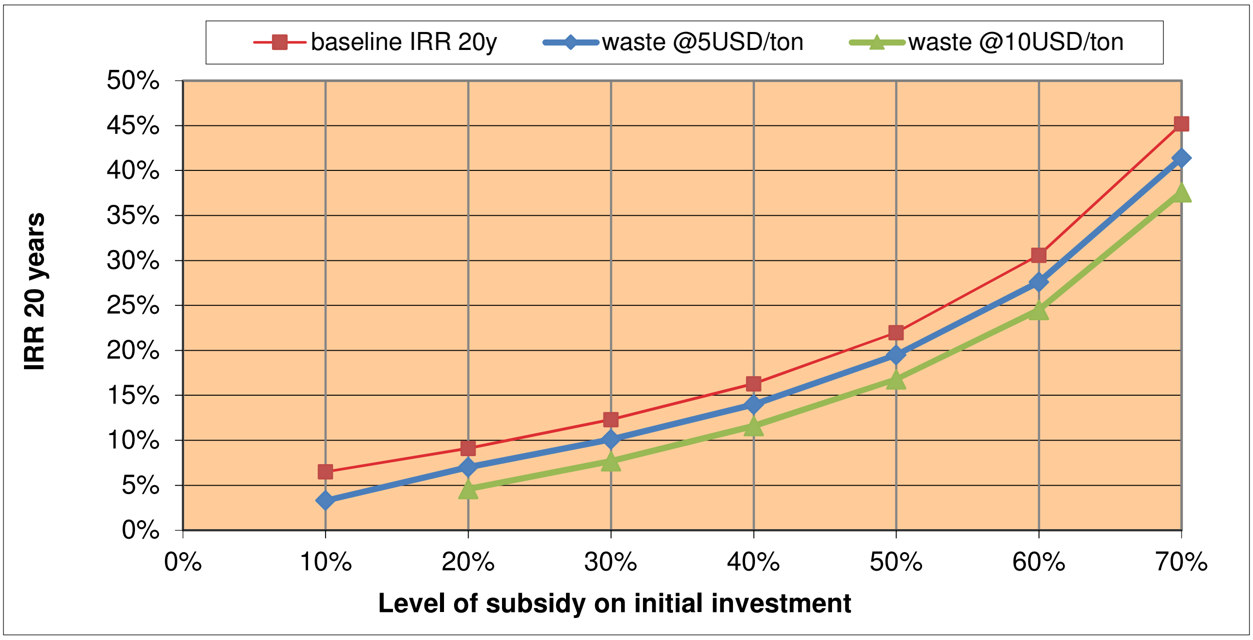


Figure 16: IRR sensitivity to subsidy on initial investment at different biomass costs

Access to carbon finance

An additional source of funding for the development of the agro residue based CHP plants can be the consideration of carbon credits that could offset some of the initial investment costs (Disch et al., 2010). To assess this option under a conservative approach, we have considered an emission factor for electricity generation (grid reference) of 0.276 kg CO2 equivalent/kWh (UNDP, 2012) and a plant operational time of 20 years.

Regarding carbon prices, there is a wide range of instruments and rates. Indeed, a recent study by the World Bank (Kossoy *et al.* 2015) points out that carbon prices vary significantly – from less than US$ 1 up to US $ 130 per tCO_2 eq., with the most optimistic being the Swedish carbon tax scheme. However, the majority of emissions (over 85%) under carbon finance schemes are priced at less than US$ 10 per tCO_2 eq.

Figure 17 shows the sensitivity of the profitability of the 1000 kWe CHP plant with increases in FiT rates under carbon credit prices of 10 and 130 US$ per tCO2 eq., both for the cases of the biomass residue being available at no cost, and at a cost of 5 US$ per tonne. Figure 18 also show the profitability vs subsidy to initial investment under carbon prices of 10 and 130 US$ per tCO2 eq. and current FiT levels.

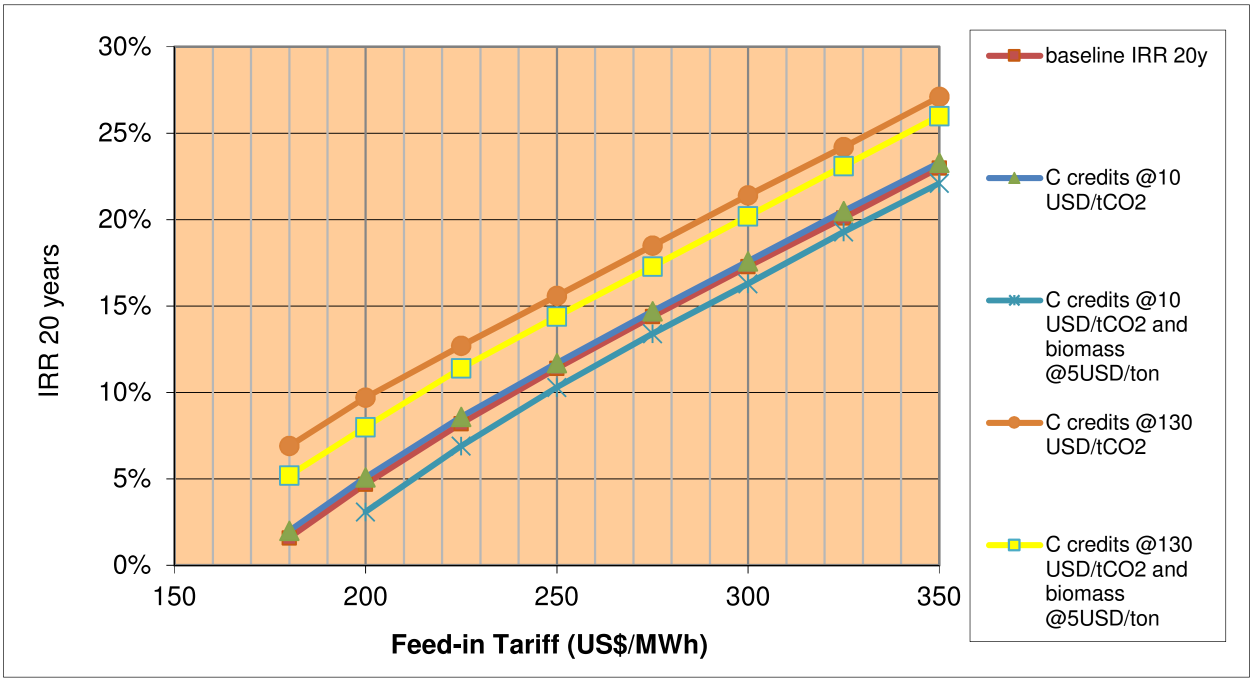


Figure 17: IRR sensitivity to carbon credits at changing FiT rates

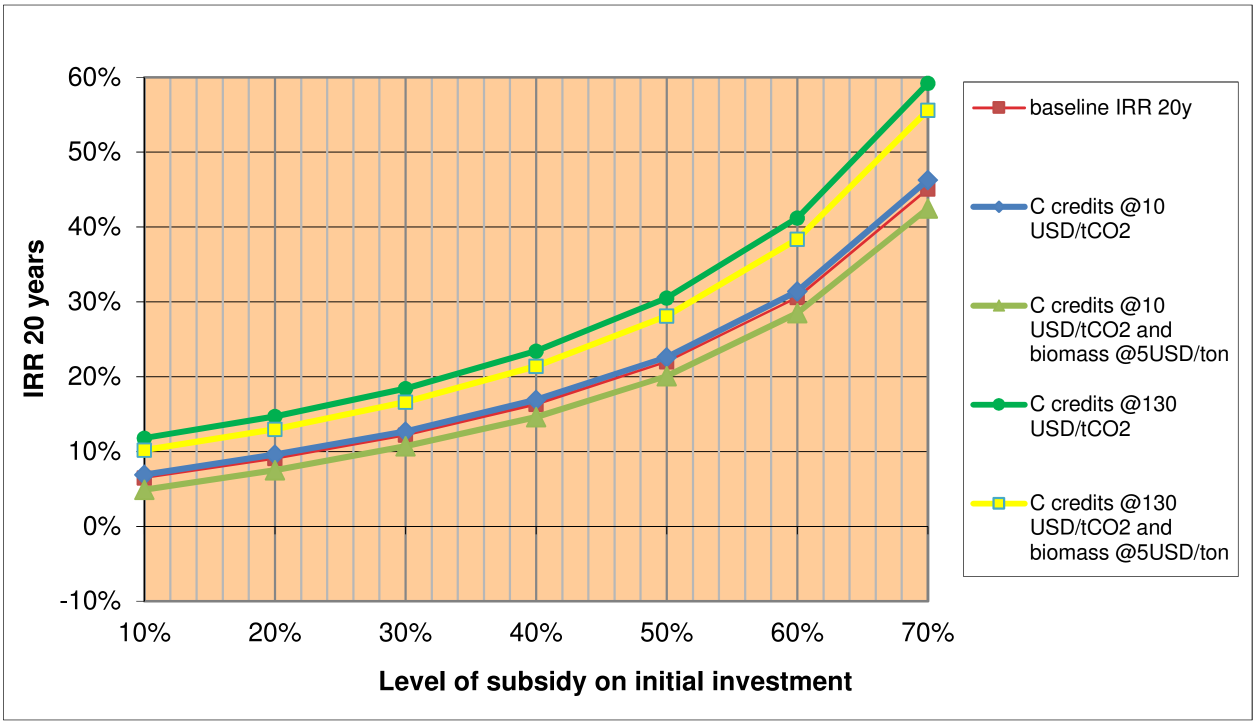


Figure 18: IRR sensitivity to carbon credits at different levels of capital subsidy

It can be noted that the consideration of carbon finance under the more probable carbon price of 10 US$ per ton CO_2 eq. currently traded in existing carbon funds would have little impact on the financial results. However, if more favourable schemes (like the Swedish carbon tax) are considered, the viability of CHP plants run on crop residue can be possible if:

- current FiT rates are increased by 8% (up to 215 US$/MWh), or
- a minimum subsidy to initial investment of 10% under current FiT levels.

Figures 17 and 18 show how some of the key ingredients can affect the profitability of biomass plants and how policy at the local, national and global level can affect investment. Ghana's renewable energy act has instituted a renewable energy fund with the objective of providing financial resources for the promotion, development, sustainable management and utilisation of renewable energy sources. Money from the fund is to be used for, inter alia, production-based subsidies and equity participation for 'mini-grid and off-grid renewable power systems for remote areas and islands' (Parliament of the Republic of Ghana, 2011). The resources available from the biomass sector present an opportunity for the country to support biomass electricity plants to contribute towards the government's aim of achieving universal access to electricity over the coming decade. This could supplement other renewable resources such as solar and wind, either as standalone technologies or as hybrid systems where appropriate, to reduce electricity storage, with the possibility to reduce overall costs.

5 Second Configuration - TRIGENERATION (POWER, HEATING AND COOLING) BASED ON RESIDUES FROM SMALLHOLDER FARMS

5.1 ABSTRACT

Many remote rural communities are ignored in rural electrification plans due to their remoteness or their relatively low demand potential. Many of those communities are rural agricultural villages that cultivate crops whose residue is a potential solid biomass fuel for power generation using appropriate technologies. This research proposes a feasibility study of trigeneration (heat, power and cold) from small farm typologies with enough clustered crop residue in selected communities in Ghana, as well as definition (prototype level) of the best generation technology. A sample of 11 districts in Ghana were surveyed in order to assess the levels of agricultural residue produced in small holder farms and their possible clustering for supplying these residues to a hypothetical centralized trigeneration plant. The results obtained in terms of plant capacity, biomass residue yields, energy output flows and economic analysis indicate good prospects for the deployment of trigeneration as a solution in rural agricultural areas of sub-Saharan Africa

This section is based on the publication:

Pol Arranz-Piera, Oriol Bellot, Oriol Gavaldà, Francis Kemausuor, Enrique Velo, Trigeneration Based on Biomass - Specific Field Case: Agricultural Residues from Smallholder Farms in Ghana, ***Energy Procedia***, Volume 93, August 2016, Pages 146-153, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2016.07.163

5.2 LITERATURE REVIEW

Producing energy from crop residues biomass would support Ghanaian smallholder farmers in several ways (KITE, 2009; Tanko, 2012): (1) they could power modern irrigation facilities to cultivate crops during the 'dry' season, using plots closer to the community where power supply could be economically extended; (2) Farmer households would have the opportunity to become suppliers of biomass resources for energy production and thereby broaden their income generation sources; (3) The introduction of electricity supply in remote rural communities would enable the use of crop handling and pre-processing machinery which will serve two main purposes: ensure that perishable produce (such as tomatoes) could be stored safely and processed before it is transported to markets; and (4) The collection and utilization of crop residues would help curb bush fires that often start with residues burnt on harvested fields and spread to forests and un-harvested fields during the dry season.

Recent projections in Ghana (KITE, 2009; Kemausuor, 2015) have shown the socio-economic benefits of promoting biogas from agro residue (cassava peels) to displace currently used firewood; the needed investments would have a 7-year Payback Period, and yield an Internal rate of return of about 19% over a 20-year analysis.

Although low-level thermal (not for cooking) and cooling requirements in these rural communities are not abundant currently, the existence of an important residual heat resource could trigger industrial development in the agro food transformation sector [4]. This could help the communities move from being merely self-sufficient communities to being able to transform part of their product (heat), store it (cold) and sell it elsewhere.

5.3 METHODS

Previous studies (KITE, 2009; Kemausuor, 2015; Brew-Hammond et al., 2008; Mohammed, 2013; Pérez-Fortes et al., 2012) have proposed that to be technically and economically feasible, crop residues must meet two important criteria: (i) they should be produced within a certain radius or distance to a central point where the energy generation plant would be located, depending on the plant generation capacity; and (ii) the energy contents of the residues must meet a certain minimum value.

Based on the determination of the availability and location of crop residues with respect to potential biomass-to-power plant sites presented in section 4 of this Thesis, this chapter considers the additional possibilities of selling the electricity produced to neighbouring residential customers, to use the waste heat (CHP), and the generation of cold (CHCP), and discuss how such scenarios would impact the financial prospects of the biomass to energy generation schemes. Moreover, the energy-water-nexus would be fostered by enabling the following applications:

- Water pumping towards the origin biomass exploitations, thus, irrigation resilience strengthening, through assurance of the resource (water/energy).
- Enabling wastewater treatment and, eventually, reuse (also for irrigation purposes), through appropriate low-cost and low-consumption techniques, such as Imhoff tanks, biodisks, infiltration-percolation, phragmytes- and algae treatment and anaerobic water/ sludge treatment (possible second energy closed-loop through biogas methane generation for heating purposes).

The adoption of this energy / water / agriculture approach, in a more direct or indirect measure, an integrated rural development impact can be boosted, especially poverty alleviation (through reinforcing the cycle agriculture-biomass production-value for waste), access to health (enabling health facilities downstream the power plant) and environmental protection (energy would be available for water distribution and / or appropriate sanitation and wastewater treatment).

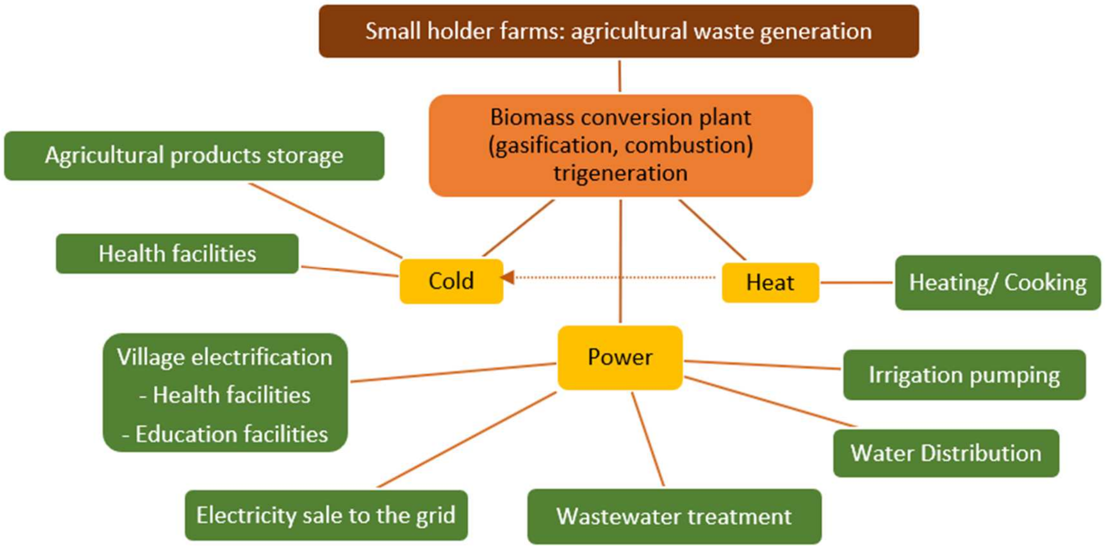


Figure 19. Biomass based trigeneration concept applied to rural communities.

As a summary, the envisaged cycle (Figure 19) would have an overall estimated energy yield of around 70% to 75%, considering the basic electrical efficiency of a gas CHP genset (25%), plus the potential heat recovery from the genset (fumes, lubricant and water circuits), which could account for another 50% (Mc Kendry, 2002; Escorcia et al., 2012). The potential interest for cooling in rural areas in Ghana makes the case for the conversion of part of this recovered heat into cold, by means of an absorption machine (with a COP of 0,66) (Escorcia et al., 2012); hence, assuming that one third of the heat would be converted into cold, we can consider a 35% heat yield plus a 10% cold yield.

5.4 RESULTS AND DISCUSSION

5.4.1 Determination of energy outputs

Stemming from the crop residues availability and related CHP plant capacities discussed in section 4 (Tables 12, 13, 14), the trigeneration outputs of 600 kWe and 1 MWe plants has been assessed in terms of:

i. electricity supply - number of households supplied, their consumption and the surplus exported to the grid;

ii. heat supply - quantity of crop residue (cassava, maize) that could be dried; and

iii. cold supply - quantity of fresh produce (tomato) that could be conserved.

The hypotheses used to account for the residual heat values have been the following:

- The value for cassava has been obtained by considering a reduction of 60% of the weight of the dried cassava residue, the calorific value of evaporated water (2.264 kJ/kg), and an energy conversion factor of 87,5% (APISA, 2016). In the case of maize residue, drying from 25% to 15% moisture content (to enable storage) is considered.
- The value for tomato storage has been evaluated using TRNSYS simulation of a refrigeration chamber in Kumasi at 14 ºC inside, using a factor of occupancy of tomatoes of 50%

Table 16: Energy output from biomass trigeneration plants

Minimum CHP plant Power output (kWe)	Number of small households directly supplied with the plant	Electricity consumed by the households (MWh/year)	Electricity to be exported to the grid (MWh/year)
600	600	720	3.480
1.000	1.000	1.200	5.800
2.000	2.000	2.400	11.600
5.000	5.000	6.000	29.000

Table 17: Use of residual heat

Minimum plant output (kWe)	**Option 1: Drying**	**1a: cassava residue**	**1b: maize residue**	**Option 2: tomato cold storage**	
	Residual heat (MWh/yr)	Yield (Tonnes/year)	Yield (Tonnes/year)	Residual cold	Yield (Tonnes/year)
600	8.400	7.636	152.920	3.480	3.480
1.000	14.000	12.727	254.867	5.800	5.800
2.000	28.000	25.454	509.734	11.600	11.600
5.000	70.000	63.636	1.274.336	29.000	29.000

5.4.2 Economic viability of CHP plants

A preliminary economic balance has been performed in order to assess the viability of CHP power plants (600kWe and 1 MWe). Private investment has been considered (at 20% yearly rate of return over a 10-year amortization time). The maximum potential cost of the crop residue (i.e., the maximum price that could be paid for the biomass to run the CHP plants) has been determined. It must be noted that the sale of both the electricity generated and a certain amount of the residual heat is needed to reach profitability.

Table 18: First economic balance of the CHP plants (first 10 years) – considering 100% heat sales

Minimum CHP plant Power output (kWe)	600	1,000
Investment cost (US $)	4,561,440	5,848,000
Annualised investment cost (d=6%, 10 years) (US $/year)	601,234	770,813
Yearly maintenance costs overheads + staff costs + maintenance costs + (20%) profit for the investor) (US $/year)	300,000	334,800
Total expenses (US $/year)	**901,234**	**1,105,613**
Electricity income (price of electricity=0.14 $/kWh) (US $/year)	588,000	980,000
Heat income (price of heat=0.06 $/kWh) (US $/year) **@100% heat sale**	504,000	840,000
Total income (US $/year)	**1,092,000**	**1,820,000**
Maximum value for crop residue sourcing (US $/year)	190,766	714,387
Tonnes of crop residue (tonnes/year)	6,679	11,132
Maximum affordable price of crop residue (US $/tonne)	**29**	**64**

Table 19: First economic balance of the CHP plants (first 10 years) – considering 60% heat sales

Minimum CHP plant Power output (kWe)	600	1,000
Investment cost (US $)	4,561,440	5,848,000
Annualized investment cost (d=6%, 10 years) (US $/year)	601,234	770,813
Yearly maintenance costs overheads + staff costs + maintenance costs + (20%) profit for the investor) (US $/year)	300,000	334,800
Total expenses (US $/year)	**901,234**	**1.105.613**
Electricity income (price of electricity=0.14 $/kWh) (US $/year)	588,000	980,000
Heat income (price of heat=0.06 $/kWh) (US $/year) **@60% heat sale**	313,234	554,400
Total income (US$/year)	**901,234**	**1,534,400**
Maximum value for crop residue sourcing (US $/year)	0	428,787
Tonnes of crop residue (tonnes/year)	6,679	11,132
Maximum affordable price of crop residue (US $/tonne)	**0**	**39**

5.4.3 Potential of Carbon Finance

An additional source of funding for the development of the agro residue-based CHP plants discussed in this paper can be the consideration of carbon credits that could offset some of the initial investment costs. To assess this option under a conservative approach, we can consider an emission factor for electricity generation (grid reference) of 0.276 kg CO2 eq./kWh (UNDP, 2012) and a plant operational time of 10 years.

Regarding carbon prices, there is a wide range of instruments and rates; a recent study published by the World Bank (Kossoy et al., 2015) points out that the carbon prices vary significantly—from less than US $ 1 up to US $ 130 per tCO2 eq.

However, the majority of emissions (over 85%) under carbon finance schemes are priced at less than US $ 10 per tCO2 eq. Using the price of 10US $ per tCO2 eq., the results shown in Table 6a do not change significantly:

Table 20: Effect of Carbon financing (first 10 years, emissions priced at 10 US $ per tCO2 eq.)

CHP plant Power output (kWe)	**600**	**1,000**
Annual electricity generation (MWh/year)	4,200	7,000
Investment cost (US $) - carbon credits at 10 US $/tCO2 eq.	4,445,402	5,654,603
Annualised investment cost (d=6%, 10 years) (US $/year)	585,939	745,322
Yearly maintenance costs overheads+ staff costs + maintenance costs + **(20%)** profit for the investor) (US $/year)	300,000	334,800
Total expenses (US $/year)	**885,939**	**1,080,122**
Electricity income (price of electricity=0.14 $/kWh) (US $/year)	588,000	980,000
Heat income (price of heat=0.06 $/kWh) (US$/year) @100% heat sale	504,000	840,000
Total income (US $/year)	**1,092,000**	**1,820,000**
Maximum value for crop residue sourcing (US $/year)	206,061	739,878
Tonnes of crop residue (tonnes/year)	6,679	11,132
Maximum affordable price of crop residue (US $/tonne)	**31**	**66**

Considering the most optimistic scenario (Sweden carbon tax scheme), the results would be:

Table 21: Effect of Carbon financing (first 10 years, emissions priced at 130 US$ per tCO2 eq.))

CHP plant Power output (kWe)	600	1,000
Annual electricity generation (MWh/year)	4,200	7,000
Investment cost (US $) - carbon credits at 130US $/t$CO_2$ eq.	3,052,946	3,333,843
Annualised investment cost (d=6%, 10 years) (US $/year)	402,402	439,427
Yearly maintenance costs overheads+ staff costs + maintenance costs + **(20%)** profit for the investor) (US $/year)	300,000	334,800
Total expenses (US $/year)	**702,402**	**774,227**
Electricity income (price of electricity=0.14 $/kWh) (US $/year)	588,000	980,000
Heat income (price of heat=0.06 $/kWh) (US$/year) @**100% heat sale**	504,000	840,000
Total income (US $/year)	**1,092,000**	**1,820,000**
Maximum value for crop residue sourcing (US $/year)	389,598	1,045,773
Tonnes of crop residue (tonnes/year)	6,679	11,132
Maximum affordable price of crop residue (US $/tonne)	**58**	**94**

This level of carbon pricing would allow a substantial reduction of the minimum residual heat sales (down to 23%) to achieve the minimum CHP plant size (600kW) viability.

Table 22: Lowest heat sales rate that would enable CHP plant viability under a Carbon financing scheme (first 10 years, emissions priced at 130 US$ per tCO2 eq. and lower heat sales)

CHP plant Power output (kWe)	600	1,000
Annual electricity generation (MWh/year)	4,200	7,000
Investment cost (US $) - carbon credits at 130US $/tCO2 eq.	3,052,946	3,333,843
Annualized investment cost (d=6%, 10 years) (US $/year)	402,402	439,427
Yearly maintenance costs overheads+ staff costs + maintenance costs + (20%) profit for the investor) (US$/year)	300,000	334,800
Total expenses (US $/year)	**702,402**	**774,227**
Electricity income (price of electricity=0.14 $/kWh) (US $/year)	588,000	980,000
Heat income (price of heat=0.06 $/kWh) (US$/year) **@23% heat sale**	115,920	193,200
Total income (US $/year)	**703,920**	**1,173,200**
Maximum value for crop residue sourcing (US $/year)	1,518	398,973
Tonnes of crop residue (tonnes/year)	6,679	11,132
Maximum affordable price of crop residue (US $/tonne)	**0**	**36**

6 Third Configuration – BIOMASS BASED MINI-GRID ELECTRICITY SERVICE FOR RURAL COMMUNITIES

6.1 ABSTRACT

The Sustainable Development Goals (SDGs) are emphatic on the role of energy for development, with a target to ensure universal access to affordable, reliable and modern energy services to about 1.3 billion people without electricity access, and to increase substantially the share of renewable energy in the global energy mix. For remote rural communities in developing countries, where grid extension is often expensive, decentralised biomass mini-grids can be a reliable electricity supply solution. This study investigated the technical and financial feasibility of decentralized electrification based on agricultural residue gasification in five Ghanaian communities. Results show that the projected electricity demand of the communities compares favourably with the potential energy generation from available agricultural residues, a situation that we envisage in many rural communities where agriculture is a predominant livelihood activity. As with most biomass electricity analysis, it is not profitable from the perspective of an entrepreneur with 100% private funding; however, by applying a customer tariff equal to the current expenditure on electricity equivalent uses in the communities, a subsidy of about 35% on initial investment would enable a private entrepreneur an internal rate of return of 15%, whereas a 60% subsidy could enable internal rate of return of 25%.

This section is based on the publication:

Pol Arranz-Piera, Francis Kemausuor, Lawrence Darkwah, Ishmael Edjekumhene, Joan Cortés, Enrique Velo, Mini-grid electricity service based on local agricultural residues: Feasibility study in rural Ghana, ***Energy,*** Volume 153, 2018, Pages 443-454.

6.2 LITERATURE REVIEW

The use of renewable energy, and indeed biomass, to provide electricity for off-grid and remote communities has been the subject of intense and interesting research across the globe (e.g., Sen and Bhattacharyya, 2014; Weitemeyer *et al*., 2015; Walwyn and Brent, 2015; Eder *et al*., 2015; Parker, 2015; Ligus, 2015; Bogdanov and Breyer, 2016; Nizami *et al*., 2017; Rahman *et al*., 2017). Different types of technologies for converting biomass into useful energy have been studied and ongoing research continue to explore these issues. Zabaniotou *et al*. (2013) studied the performance of gasification systems with internal combustion engine on different agricultural residues and found that different biomass types had different effects on gasification parameters and process efficiency. A similar study by Leu (2010) explored small-scale solid biomass power systems based on direct coupling of an updraft fixed bed gasifier with a Stirling engine. Andrew *et al.* (2016) studied the characteristics of biomass steam gasification in an indigenously designed rotary tubular coiled-downdraft reactor for high value gaseous fuel production from rice husk. The reactor system enhanced biomass conversion to gaseous products by improved mass and heat transfer within the system induced by a coiled flow pattern with increased heat transfer area. They also investigated the effects of reactor temperature, steam-to-biomass ratio and residence time on overall product gas yield and hydrogen yield. Other researchers have explored co-gasification using biomass blends with non-biomass based fuels such as coal. For example, Hegazy *et al.* (2017) investigated co-gasification of Egyptian Maghara coal and rice straw blends using entrained flow gasifier technology and found this to be technically feasible. Others have conducted research on natural gas and biomass systems (Pantaleo *et al.*, 2017), as well as other related resources (Bombarda and Invernizzi, 2015). The utilisation of the by-products of biomass conversion technologies has also been explored. One such study modelled the utilisation of char and flue gases for further energy production by reforming them into secondary producer gas by means of a secondary reactor and capturing the waste heat to optimize the process using heat exchangers (Vakalis, 2016).

Beyond the technological issues, other key research in the area have had to do with biomass supply and financial feasibility of biomass conversion technologies in different locations and capacities (Sansaniwal *et al.*, 2017; Yazan *et al.*, 2016). Pantaleo *et al.* (2015) found that the energy performance and profitability of biomass plants, and the selection of the optimal conversion technology and size, are highly influenced by the typology of energy demand (load-duration curve, electricity load patterns, etc.). In relation to the technology and system costs, Thanarak (2012) also investigated the cost of raw fuel collection and processing costs, transportation costs, electricity prices, prices of agricultural products, price level of agricultural residue, fuel prices, employment and the business of producing biomass energy in Thailand, concluding that models are needed to explore these issues further in other countries.

The aim of this case study, therefore, is to apply the integrated planning methodology presented in section 3 by obtaining primary data at the community level and investigating the technical and financial feasibility of off-grid electricity services based on agricultural residue. The specific objectives of the case study are to (1) assess the potential of biomass at the community level for electricity generation; (2) estimate electricity demand at the community level; (3) assess the suitability of communities for mini-grids, based on criteria such as electricity demand, inter-household distances, size of community and distance from the existing grid; and (4) assess financial viability. In performing the financial viability, different scenarios are presented in relation to government support on capital expenditure, biomass supply cost, and tariffs.

6.3 MATERIAL AND METHODS

6.3.1 Study Communities

The study was conducted in Ghana, West Africa. Five rural communities were selected for the study, based on previous experience with Multi-Functional Platforms (MFPs) (Kemausuor et al., 2011) and several field visits that were carried out in the period 2013-2016. Three of the communities, Seneso, Bompa and Boniafo are located in the Atebubu-Amantin district of the Brong Ahafo Region, whereas Nakpaye and Jaman Nkwanta are respectively located in the East Gonja and Kpandai districts of the Northern Region of Ghana (see map in Figure 20).

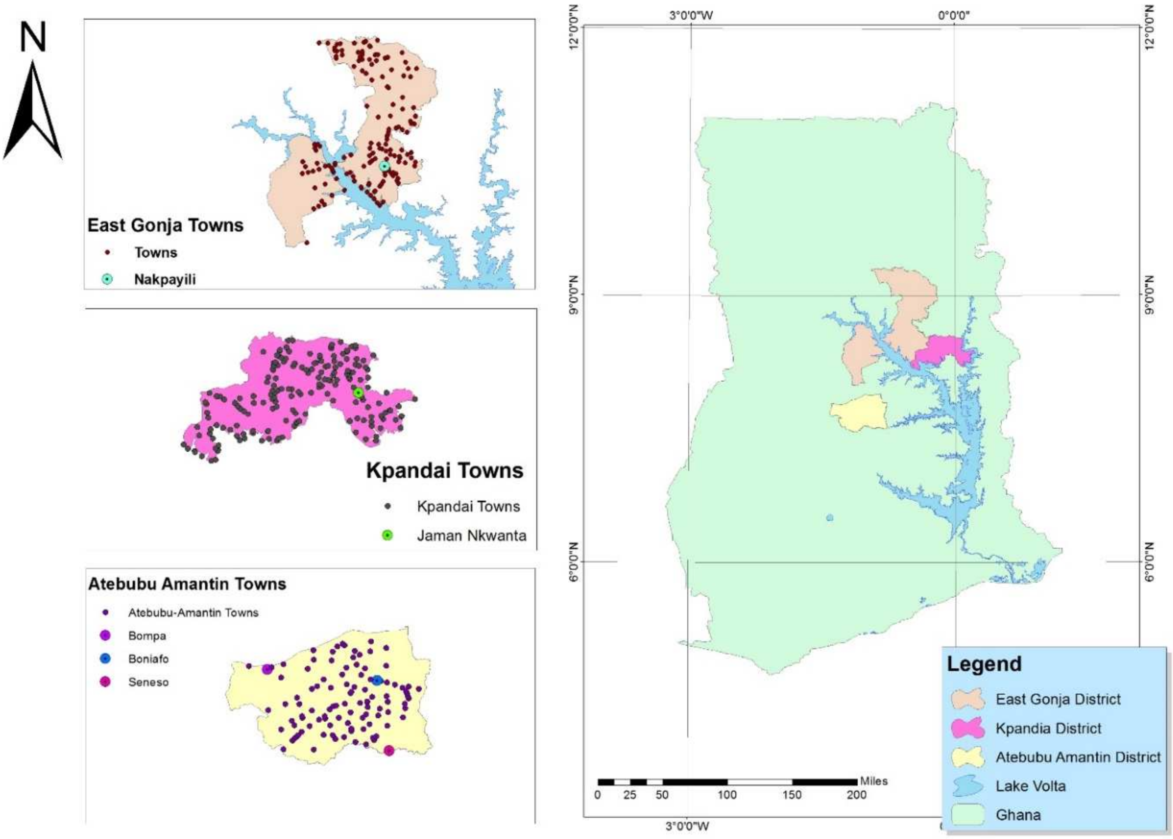


Figure 20: The five Ghanaian rural communities that participated in this study

6.3.2 Study Approach

First Phase

The first Phase of the study consisted of a general analysis of the project, and data collection. It involved a desk review of available information for the study communities and preliminary visit to familiarise with the communities and their leadership structure. Thereafter, data was collected by conducting a series of surveys in the communities.

Unlike existing studies on rural electrification in Ghana and West Africa, this study relied more on primary data collected from the field, as opposed to using secondary data. Primary data collection occurred through field visits. Details of sampling for the survey is shown in Table 23.

Table 23: Sampling for survey in five communities

Community	Population	No. of households	Households interviewed	Farmers interviewed
Seneso	528	56	22	12
Bompa	614	63	25	17
Boniafo	635	68	25	19
Nakpaye	894	55	23	19
Jaman Nkwanta	586	71	25	22
Total	3,257	313	120	89

Second Phase

In the second Phase of the study, detailed calculations were made on different aspects of the proposed community mini-grids, using the data collected in the first phase. The communities were then ranked based on the results of this assessment, using a scale developed to reflect the relative feasibility of the project in these localities. The ranking methodology could aid policy makers and planners when faced with a decision to prioritise communities for mini-grid electrification. Factors considered in the analysis were socio-economic factors, technical and technological factors, and financial factors.

6.3.3 Data Collection and Analysis

6.3.3.1 Socio-economic Assessment

Phase 1 of the socio-economic assessment consisted of a community appraisal. Each of the 5 communities were visited and assessed in terms of the demographics: population, housing characteristics and economic activities. Primary data was collected for all these indicators.

All the communities are predominantly farming communities. Other economic activities include, trading, charcoal production, cattle rearing (for communities in the Northern Region) and fish mongering (for communities in the Brong Ahafo region).

In Phase 2, analysis of electricity demand was undertaken, based on the activities of the community. The estimation of current as well as future demand was based on four (4) main load categories in a mini-grid (IFC-ERC, 2015 and GDEE, 2015): residential, institutional, commercial and industrial.

The residential consumption includes private households (HHs) where energy is consumed primarily for lighting and as input for the provision of other services (including room conditioning, refrigeration, entertainment/communication, etc.). Residential consumptions have been segmented further into four (4) consumption classes defined primarily by the consumption profile of residential customers found within recent mini-grid projects implemented by the Ghana Ministry of Energy (TTA, 2017).

Institutional consumption represents the consumptions of public institutions in the community. Public lighting, public water pumping, energy use in religious buildings, schools and health centres have been considered in this category. Consumption levels for this category are derived from the field surveys and the demographic and social characteristics of each community.

Commercial consumption represents the potential electricity to be consumed by commercial bodies identified during the field surveys and these include: dressmaking, mini-shops, drinking bars, hairdressing salons, etc. Their consumption is related to each community's characteristics. Industrial consumption represents the potential electricity to be consumed by small industrial concerns identified in the field surveys such as the MFP operation. The consumption depends on the operational cycle of the particular industry.

The estimated electricity demand for each category is then aggregated to give the projected total energy consumption for the first year of the planning period. In determining how the yearly consumption and peak demand will evolve year by year over the projected planning period, three scenarios have been considered:

- The Baseline Scenario estimates the potential electricity consumption in the five (5) communities, assuming these communities had access to electricity at the time of the study. The baseline electricity consumption was based on energy consumption patterns found within projects implemented by the Ghana Ministry of Energy (TTA, 2017), with similar socio-economic characteristics.
- Alternative Scenario 1 considers the evolution of yearly consumption and peak demand over the period 2017-2027, driven by population growth. Population growth rate has been factored in as 5% annual increase in household connections, as per the results of the field interviews and the latest GLSS Ghana Living Standards Survey available (GLSS, 2014). In this scenario, yearly consumption (and peak demand) is projected to increase as population of the communities increases. The increase in consumption will be accounted for by increases in household demand, school demand

(as result of increased demand for lighting and in most cases demand for computing services) and the demand for more public lighting.

- Alternative Scenario 2 projects the evolution of yearly consumption and peak demand over the planning period (2017-2027) due to population growth and a socio-economic growth to be experienced in the communities, largely attributed to the provision of electricity. The improvement in the socio-economic status of community members and businesses is expected to give rise to increases in household demand (particularly in the demand categories that include the utilisation of a fridge or a freezer), in commercial demand (as a result of new businesses springing up and existing ones acquiring more equipment, etc.) and in institutional demand (as a result of the use of more and better equipment/appliances in these institutions and the establishment of health centres, which were not considered in the baseline scenario) (ESMAP, 2016). For this scenario, the household distribution into consumption classes is taken from a similar but grid-connected rural community (meter readings facilitated by the local utility, Northern Electricity Distribution Company Limited (NEDCO) in the Brong-Ahafo region.

6.3.3.2 Organizational and Institutional analysis

Mini-grids are recognized in Ghana's energy policies as an adequate solution to contribute to achieving universal access to electricity in the country, especially for populations living on islands in Lake Volta and in isolated lakeside or inland locations (Kemausuor and Ackom, 2016).

There are currently five solar energy based mini-grids pilot projects in Ghana (TTA, 2017), that have motivated a preliminary mini-grid specific policy formulation released in January 2016. This formulation set a public sector, top down arrangement, where Ghanaian public utilities will be or are expected to be responsible for the ownership and management of mini-grids developed with public funds. It is expected that the successful proliferation of mini-grids across rural Ghana will require the adoption of specific policy procedures, technical standards and regulations, including the possibility for private developers to build, own and operate mini-grids under a license issued by the Energy Commission, the energy regulatory body.

This study has paid attention to the identification of which actors could play the roles described in Table 4 as part of the proposed planning framework (section 3). The results are shown in Table 24.

Table 24: Identification of main actors within the proposed planning framework in Ghana

KEY ROLES	Case A: Current policy for public mini-grids (Top down approach)	Case B: Private developer model (Bottom-up approach)
Programme or Project Developer	Ministry of Energy	Private entities (whether profit or non-profit)
Institutional developer	Ministry of Energy	District Assemblies
Regulators	Energy Commission Public Utilities Regulatory Commission	Energy Commission
Standardising agent	Energy Commission	Energy Commission
Funder(s)	Government of Ghana, International Donors	Private entities
Users	Rural or Isolated Communities	Rural or Isolated Communities
Social developer	District Assemblies	Community councils NGOs
Technical director or Implementer	Volta River Authority (VRA) Northern Electricity Distribution Company (NEDCO) Electricity Company of Ghana (ECG) or Certified contractors	Private contractor
Generator(s)	VRA	Private entities
Electricity service operator(s)	NEDCO ECG	Private entities
Installer	Certified subcontractor	Private subcontractor
Maintenance provider	VRA, NEDCO, ECG	Local subcontractor
Biomass supplier(s)	Community Association, Farmers, Agricultural Extension officers	Community Association, Farmers, Agricultural Extension officers
Infrastructure provider(s)	Certified suppliers	Private suppliers
Trainer – Communicator	Ministry of Energy Certified contractors	Private entities
Evaluator or Inspector	Energy Commission	Energy Commission
Dissemination director	Ministry of Energy Certified contractors	Private subcontractor NGOs

6.3.3.3 Technical and Technological Assessment

Previous studies on rural electrification have flagged the reduction of logistic problems and the convenient economics of considering distributed power generation facilities as close as possible to locations where biomass is abundant (Asadullah, 2014). In Phase 1 of our technical analysis, the availability of local biomass residues was investigated. Based on data collected in farmer fields, the overall quantities of crop residue that could be available were estimated, with consideration for alternative uses as spelt out in Blanco-Canqui and Lal (2009). Reference values on residue to product ratios (RPR) were obtained from previous studies in Ghana (Kemausuor *et al.*, 2016; Ayamga *et al.*, 2015) to estimate crop residue availability. Lower Heating Values (LHV) for energy potential estimation were obtained from Arranz-Piera, *et al.* (2017); Kemausuor (2015); Thomsen *et al.* (2014); Duku *et al.* (2011); Jekayinfa and Scholz (2009).

In Phase 2 of the technological analysis, the present and future electricity demands are computed, and then compared to the electricity supply available from biomass, in order to ascertain the possibility of satisfying energy demand solely from agricultural residue.

The next step assessed the technical feasibility of providing energy using only biomass feedstock. Previous reviews have identified gasification as the most promising small scale (below 100kW) solid biomass to electricity conversion technology (Mohammed *et al.*, 2013, Gonzalez *et al.*, 2015). To assess electricity production potential, a reference efficiency conversion factor of 18% was applied, using a downdraft fixed bed gasifier coupled to an Otto engine gas generator set (Mazzola, 2016; Dasappa, 2011). Recent studies on small scale gasification experiences in rural Africa (Owen and Ripken, 2017) have pointed out the importance of proper O&M for a reliable operation of this technology.

The conversion technology considered in this paper is a fixed bed, downdraft gasifier coupled to a gas engine and alternator. A commercial unit from HUSK Power Systems Pvt. Ltd has been used as a reference, which comprises a gas cleaning and cooling system. Downdraft gasifiers have the lowest particle and tar content production ratios among the small-scale gasification technology options (Sansaniwal et al., 2017). The gasifier reactor has an integrated hopper and a biomass feedstock inlet valve system to ensure tightness and avoid dust release. At the bottom of the gasifier, ash is collected via a wet discharge circuit to prevent fly ash and dust emissions. The gas cleaning unit consists of a particle precipitator (cyclone) and two filters to prevent the release of air pollutants.

6.3.3.4 Financial Assessment

The financial assessment is an essential part of the final decision-making process. The financial viability analysis of the project was conducted to determine how the project will fare under various scenarios, by modelling a 20-year cash flow analysis of the mini-grid service performance. The Net Present Value (NPV) and the Internal Rate of Return (IRR) were the indicators used to measure the viability of the project. Sensitivity analyses were also conducted by varying the funding sources mix (Grant vs Private equity), the potential cost of biomass (no cost, US$ 5 or 10 per tonne) and electricity selling tariffs against the NPV. Table 25 shows the assumptions made in conducting the financial analysis (TTA, 2017; IRENA, 2012; Owen and Ripken, 2017).

Table 25: Parameters and values used in financial analysis

Parameter	**Value**	**Unit**
Estimated investment costs		
Biomass gasifier power plant (including a fixed bed downdraft gasifier, cleaning unit and gas cogenerator CHP)	2,400	US$/kW
Battery bank (lead-acid, OPzS)	90	US$/kWh
Bi-directional inverter, monitoring system and protections	720	US$/kW
Distribution lines (cabling low voltage, single phase)	3,930	US$/km
Public lighting (poles and LED fixtures)	7,800	US$/km
Engineering and construction management cost	880	US$/kW
Powerhouse construction	15,000	Unit
Installation and training works	530	US$/kW
Logistics	725	US$/kW
Replacement costs *Batteries and gasifier parts at year 10, CHP engines overhauling every 5 years, and corresponding transport costs*	31%	Over initial investment costs
Staff cost (Management, Operation)	5,500	US$/year
Maintenance (spare parts) cost	2,200	US$/year
Total M&O&M	7,700	US$/year
Biomass cost	0 / 5 / 10	US$ / tonne
Discount rate	6% (U.S. Dollar denominated)	
Inflation rate	4% (U.S. Dollar denominated)	
Project lifetime	20 years	
Minimum profitability for Equity investors	15% IRR	

6.4 RESULTS AND DISCUSSION

6.4.1 Biomass Resource Availability and Electricity Generation

The annual quantity of agricultural residues generated in each community is presented in Table 26, together with their calorific values. The assessment established that between 211 and 586 tonnes of agricultural residues are generated in the communities annually, which can be converted to electricity using a biomass gasification technology (Mazzola, 2016; Dasappa, 2011).

Table 26: Annual crop residue production in each target community

	Estimated Crop Residue (kg) per year					***Assumed moisture content (%, wet basis)**	**Lower Heating Value (MJ/kg) (*)**
Type of Residue	**Seneso**	**Boniafo**	**Bompa**	**Jaman**	**Nakpaye**		
Maize stalk	171,477	261,942	92,895	67,910	40,339	15.02	17.71
Maize cob	57,159	87,314	30,965	22,637	13,446	8.01	19.32
Maize husks	68,591	104,777	37,158	27,164	16,136	11.23	17.22
Beans Straw	49,958	2,046	24,631	29,184	25,648	16.45	12.38
Beans shells	13,322	546	6,568	7,782	6,840	16.45	15.60
Groundnut straws	44,234	39,466	29,406	18,761	12,629	18.86	17.58
Groundnut shells	9,786	8,731	6,506	4,151	2,794	13.82	17.43
Rice straw	3,205	10,050	118,839	5,752	19,173	15.50	15.56
Rice husk	534	1,675	19,807	959	3,195	13.01	13.04
Cassava stalks	4,692	28,523	6,306	19,851	20,179	20.00	17.50
Millet straw	-	-	788	6,040	6,723	63.57	15.51
Guinea Corn straw	-	-	-	-	2,096	61.80	17.00
Yam Straw	8,935	40,711	103,765	222,727	42,147	15.00	10.61
TOTAL (kg)	**431,891**	**585,781**	**477,633**	**432,918**	**211,346**		

*Values obtained **from** experiments conducted in Ghana and elsewhere by Arranz-Piera, *et al.* (2017); Kemausuor (2015); Thomsen *et al.* (2014); Duku *et al.* (2011); Jekayinfa and Scholz (2009).

Considering the LHV stated in Table 26, and a biomass to electricity conversion efficiency of 16% (adaptation from Dasappa, 2011, based on information from commercial plants developed by HUSK Power Systems Pvt. Ltd. in India, Uganda and Tanzania), the potential power that can be generated from the crop residues available at each target community is calculated and shown in Table 27 (additional calculations are provided in Appendix 3). Maize residues dominate electricity generation potential, ranging from 35 to 74% of the total electricity potential.

Table 27: Potential electricity generation from crop residue in each target community

Community	Monthly Electricity yields (kWh/month)*	
	All crops	Maize only
Seneso	27,148	19,710
Boniafo	37,476	30,109
Bompa	26,858	10,678
Jaman Nkwanta	21,847	7,806
Nakpaye	11,952	4,637

* efficiency conversion factor (biomass to electricity) of 16% (adaptation from Dasappa, 2011 based on information from commercial plants developed by HUSK Power Systems Pvt. Ltd. in India, Uganda and Tanzania).

6.4.2 Electricity Demand Projections

Electricity demand projections were made using data obtained from the communities' surveys, as well as demand segmentation observed from pilot mini-grids in the country.

Table 28 shows the demand segmentation patterns being observed at the Ghana Ministry of Energy piloted mini-grids (TTA, 2017. Peters and Imboden, 2017), and the corresponding categorisation under the energy availability quality factors developed by the U.S. National Renewable Energy Laboratory (NREL, 2016).

Table 28: Reference mini-grid customer demand segmentation for baseline and scenario 1

Demand profile*	Correspondence with Energy Service Levels by NREL	Baseline & scenario 1 (% of households)	Scenario 2 (% of households)
VL	Level 1-2	17	10
L	Level 2	63	30
M	Level 3	15	40
H	Level 4	5	20

*Very Low (VL): HHs consuming up to 20 kWh/month. Households in this category are expected to use electricity for only basic lighting and very small communications appliances like radios or mobile phone chargers.

Low (L): HHs consuming between 20 and 50 kWh/month. Households in this category are expected to use fan and/or TV in addition to the VL load.

Medium (M): HHs consuming between 50 and 100 kWh/month. Households in this category are expected to add small refrigerators in addition to L load.

High (H): Households consuming more than 100 kWh/month.

Table 28 indicates that 95% of potential customers (mainly households) would be consuming up to 100 kWh/month (VL, L and M categories) in the Baseline Scenario and Scenario 1. In scenario 2, households will evolve from their respective categories to the nearest demand categories due to increase in energy consumption (with the highest increase given in the M category, that enables the use of a fridge or a freezer). As a result, the potential customers consuming up to 100 kWh/month are expected to decline to 80% while the number of households consuming above 100 kWh will increase to 20%.

The daily load profiles have been defined by a percentage distribution of energy consumed in hourly periods for the different demand categories (TTA, 2017; Peters and Imboden, 2017). Detailed demand data for the Seneso community is shown in Table 29 and Appendix 2. Summary for all the five communities is shown in Table 30. Load profiles have been defined to ensure correct sizing of the micro power plant and mini-grid in each community.

Table 29: Electricity demand projections (case of Seneso community)

Electricity demand in SENESO community		**Baseline Scenario**	**Scenario 1 (population growth)**	**Scenario 2 (Scenario 1 + economic growth)**
Residential	HHs VL (<20 kWh)	100	160	100
	HHs L (<50 kWh)	1225	2110	1025
	HHs M (<100 kWh)	600	1080	2925
	HHs H (>100 kWh)	300	480	1900
	Total (kWh/month)	2225	3830	5940
Institutional (kWh/month)		1640	1950	2070
Commercial (kWh/month)		50	50	370
Industrial (kWh/month)		470	470	960
Total (kWh/month)		4385	6300	9340
Total (kWh/day)		**144**	**207**	**307**
Peak power demand (kW)		**15.1**	**23.5**	**33.5**

Figure 21 shows load profiles for Seneso Community for the Baseline in 2017 and Scenario 2 in 2027.

Table 30: Demand forecast for the five communities

Community	Electricity (kWh/month)			Power peak (kW)		
	Baseline	Scenario 1	Scenario 2	Baseline	Scenario 1	Scenario 2
Seneso	4385	6300	9340	15.1	23.5	33.5
Boniafo	3443	5595	8126	12.7	22.5	29.7
Bompa	5422	9602	12972	21.2	40.4	53.4
Jaman Nkwanta	5174	8822	11683	18.9	35.8	47.3
Nakpaye	2938	4076	6147	8.4	13.5	18.1

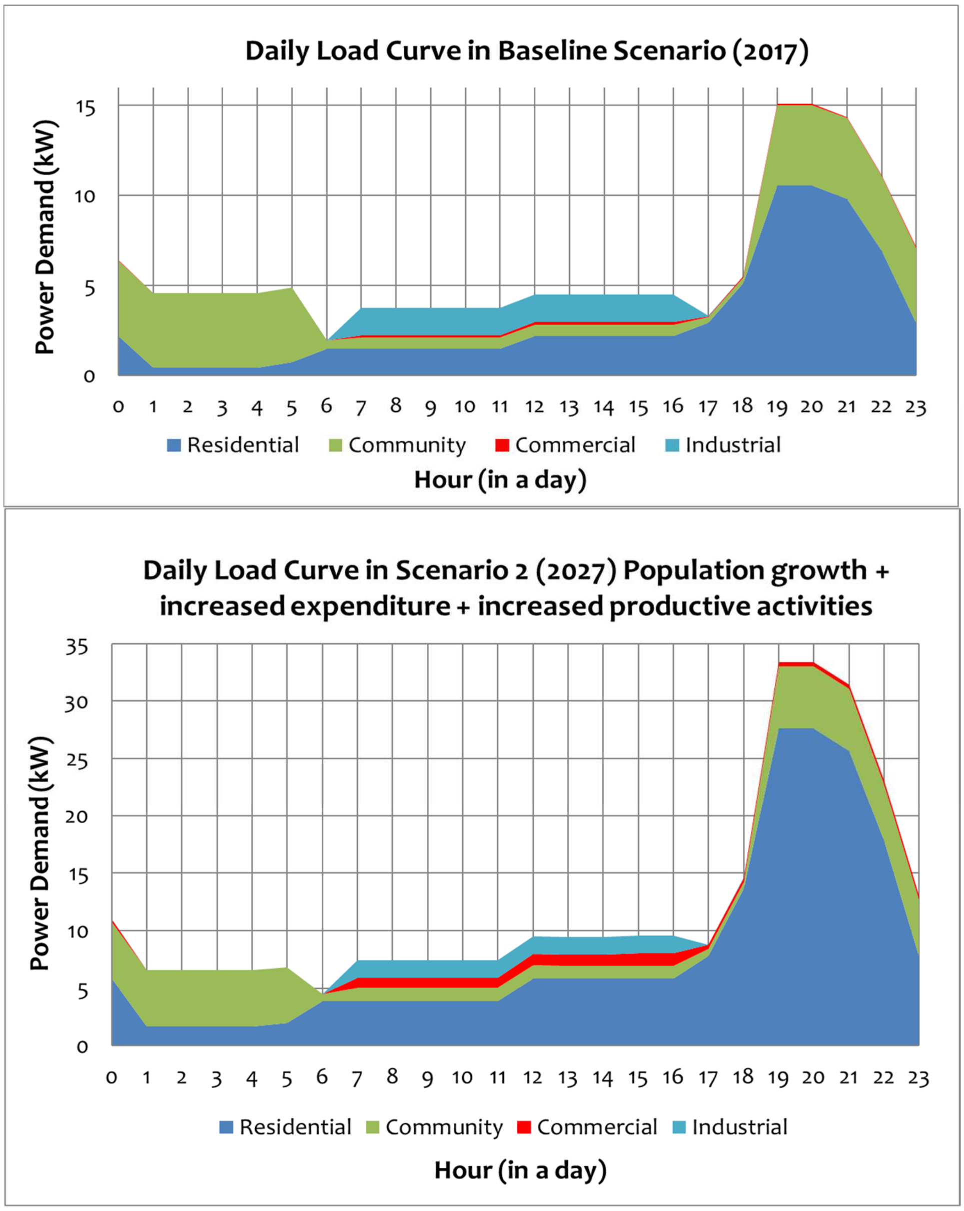


Figure 21: Projected load profiles for the Seneso Community: Baseline Scenario (top), Scenario 2 (bottom)

Typical of the national situation in Ghana, peak demand occurs between 6:00pm and 11:00pm, the period between close of daily activities and bedtime (Energy Commission, 2016). Residential demand dominates, also typical of the national picture (Energy Commission, 2016).

Figure 22 shows electricity demand values compared with the potential electricity generation from the biomass resources available within the communities (Table 27). For all three scenarios, electricity potential from the available biomass is higher than the demand computed. In the Boniafo, the potential electricity from biomass is about 4 times the electricity demand from scenario 2.

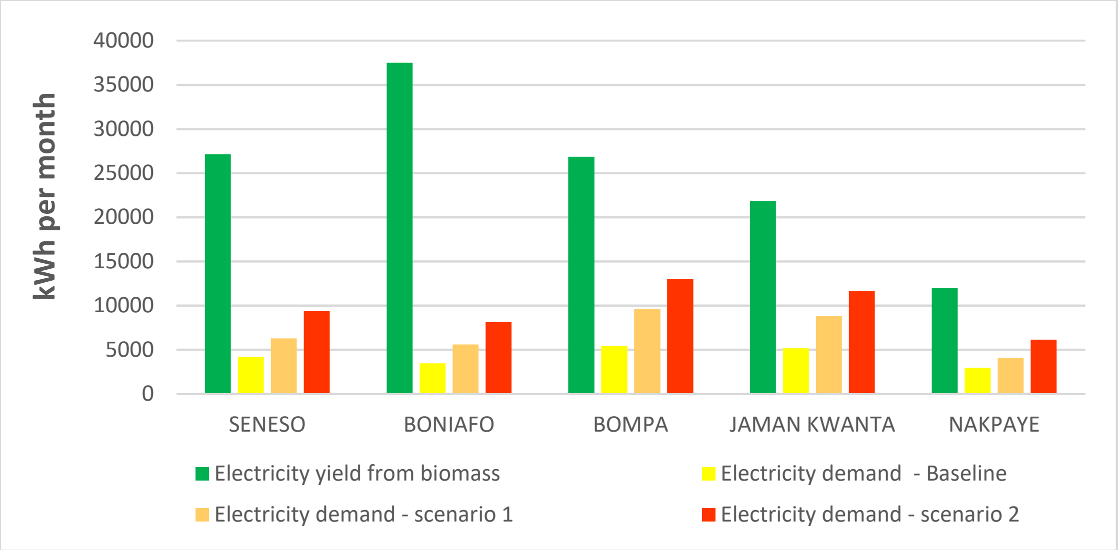


Figure 22: Summary of the electricity generation potential from crop residues compared to the electricity demand in each target community

6.4.3 Technical and Operational Feasibility Benchmarking

Combining the aspects investigated in the biomass resource assessment and the socio-economic analysis, the communities were ranked in terms of ease of implementation of biomass technology for electricity generation. An evaluation methodology was developed to assign scores to the communities based on the criteria developed in Table 31. Each criterion was scored on a scale of 1 (low) to 4 (very high). The criteria for evaluation are heavily dependent on the community typology, thus inter-household distances, radius of the community, and distance from the existing grid.

Weights were given to each criterion depending on its position on the priority scale (Table 31). An overall score above 3.5 was given a high feasibility rating, and a score below 1.9 given a low score. In between the two were medium (between 2 and 2.9), and high (between 3 and 3.4). As shown in Table 36, only one community had a *very high* score, with two others scoring a *high*, and the remaining two scoring a *medium.* None of the communities had a low score.

Table 31: Criteria for the feasibility weighted scoring

Scoring values		**Criterion: Community topology. Weight: 20%**
1	low	dispersed HHs: interdistance > 100 m, overall radius > 2 km; distance to grid < 5km
2	medium	clustered HHs: interdistance < 100 m, overall radius < 2 km; distance to grid < 5km
3	high	clustered HHs: interdistance < 50 m, overall radius < 1 km; distance to grid > 5 km
4	very high	clustered HHs: interdistance < 30 m, overall radius < 500 m; distance to grid > 5km
Scoring values		**Criterion: Current energy use and expenditure. Weight: 20%** ***1US$ = 4 GHS (April 2017)***
1	low	Average expenditure < 10 GHS/month. No community uses, No productive uses
2	medium	Average expenditure < 30 GHS/month. No community uses, No productive uses
3	high	Average expenditure > 30 GHS/month. No community uses, No productive uses
4	very high	Average expenditure > 60 GHS/month. Community & Productive uses, Experience with electricity
Scoring values		**Criterion: Potential generation from biomass residue. Weight: 40%**
1	low	< 10% electricity demand, worst case scenario
2	medium	> 30% electricity demand, worst case scenario
3	high	> 70% electricity demand, worst case scenario
4	very high	> 90% electricity demand, worst case scenario
Scoring values		**Criterion: Management model prospects. Weight: 20%**
1	low	Community not organised: no basic O&M nor Administration capacity
2	medium	Some organisation: no basic O&M nor Administration capacity
3	high	Some organisation, basic Administration capacity or basic O&M capacity
4	very high	Community well organised, basic O&M capacity and basic Administration capacity

Table 32: Technical and Operational feasibility results

	Seneso	**Boniafo**	**Bompa**	**Jaman Nkwanta**	**Nakpaye**
Community topology	4	3	4	4	2
Current energy use and expenditure	3	2	3	3	3
Potential generation from biomass residue	4	4	3	2	3
Management model prospects	4	3	2	2	2
Overall (weighted) rating	3.8	3.2	3.0	2.6	2.6
Feasibility score	very high	high	high	medium	medium

Finally, the engineering outline of the mini-grids was carried out, considering a hybrid biomass syngas genset supply architecture (with batteries), as described in Figure 23.

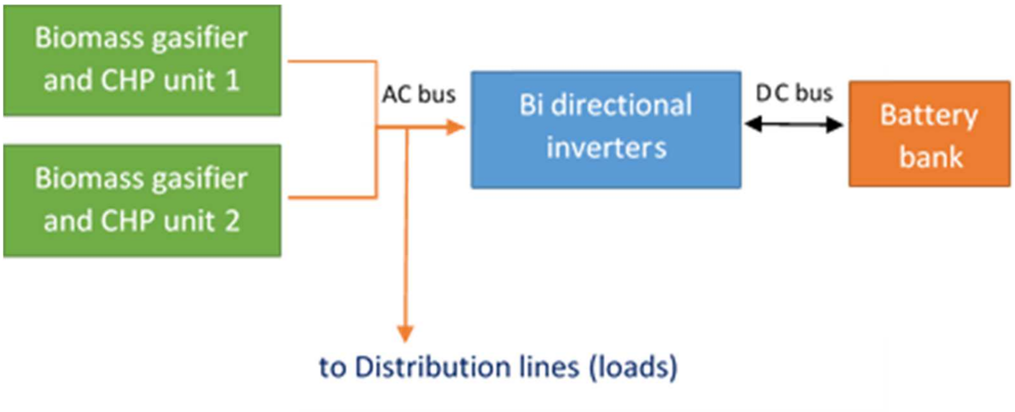


Figure 23. Block diagram of biomass hybrid generation architecture

Tables 33 and 34 show the general operating conditions and technical specifications respectively, of the mini-grid design for the community of Seneso, which had the *very high* score. Additional calculations of the load factor are provided in Appendix 1. The proposed distribution mini-grid for the Seneso community is shown in Figure 24.

Table 33: General Operating conditions used to model the mini-grid case for Seneso

Electricity service supply	307 kWh per day. Availability: 24 hours a day, 7 days a week
Powerhouse gross active electric power	34 kW in AC (50Hz)
Powerhouse configuration	2 gasifier based CHP systems, for direct electricity supply to the mini-grid and battery charging
Electricity supply configuration and operational regime	Gasifier maximum operation of 9 hours per day (reported by manufacturers), at 16% electrical efficiency (conservative estimation) Gasifier 1 - operating 2pm to 11pm Gasifier 2 - operating 10am to 2pm, and 7pm to 12pm Batteries – 0am to 10am Average daily load factor: 74.9% (Appendix 1)

Table 34: Technical specifications and CAPEX of the mini-grid case for Seneso

Component	**Value**	**Unit**	**Reference manufacturer**	**Reference investment cost (US$)**
Biomass gasifier (downdraft) CHP plant	2x17	kW	HUSK POWER	81,600
Lead-acid Battery bank	90	kWh	SUNLIGHT RES OPzV	8,000
Inverter (bi-directional)	2x5	kVA	STUDER (with a 30-minute peak load supply of 12kVA)	6,400
Monitoring system	1	unit	TTA	800
Powerhouse (3 rooms) with fence	30	m^2	Local builders	15,000
Distribution lines (aerial)	1,500	m	TTA	5,900
Public lighting (LED)	60	poles	TTA	11,700
User connection, smart meters and indoor wiring	140	users	TTA	22,400
Installation	Based on TTA references			13,000
Logistics	Based on TTA references			24,600
Project Development	Based on TTA references			35,000
Total CAPEX US$				**224,400**

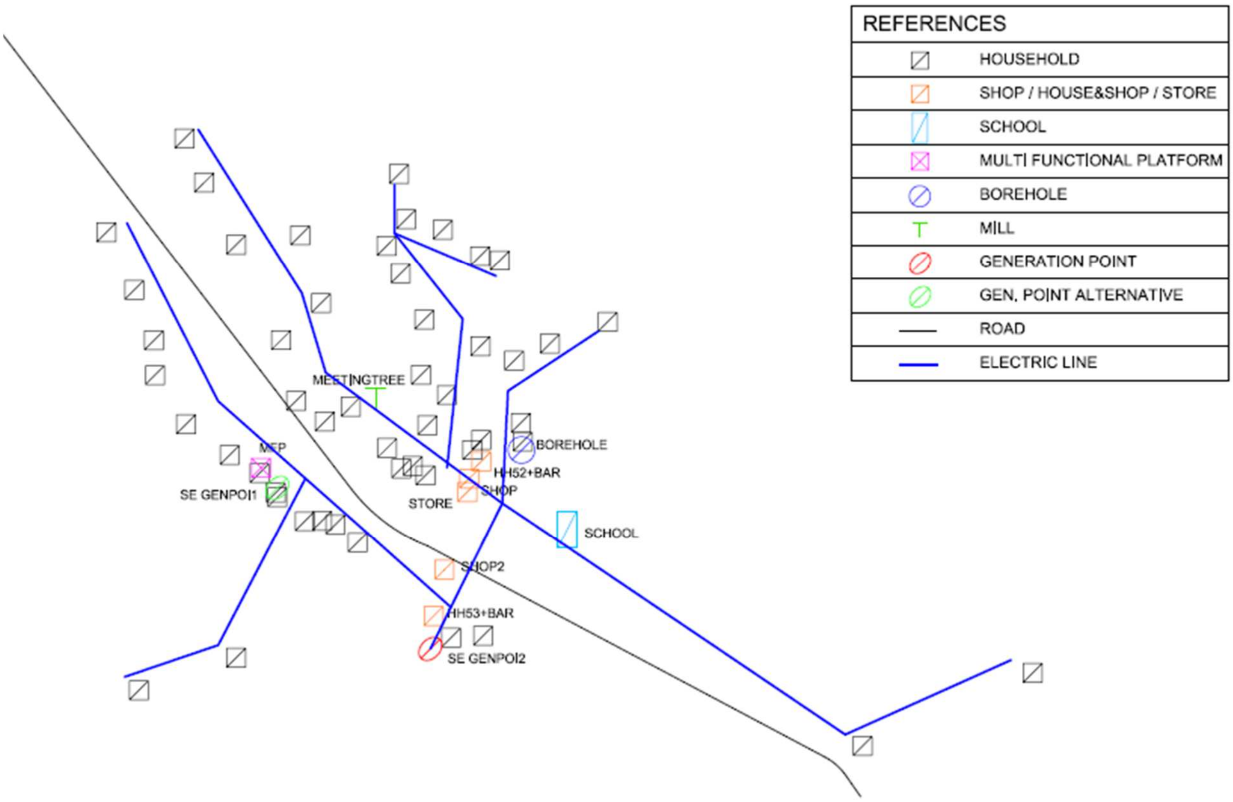


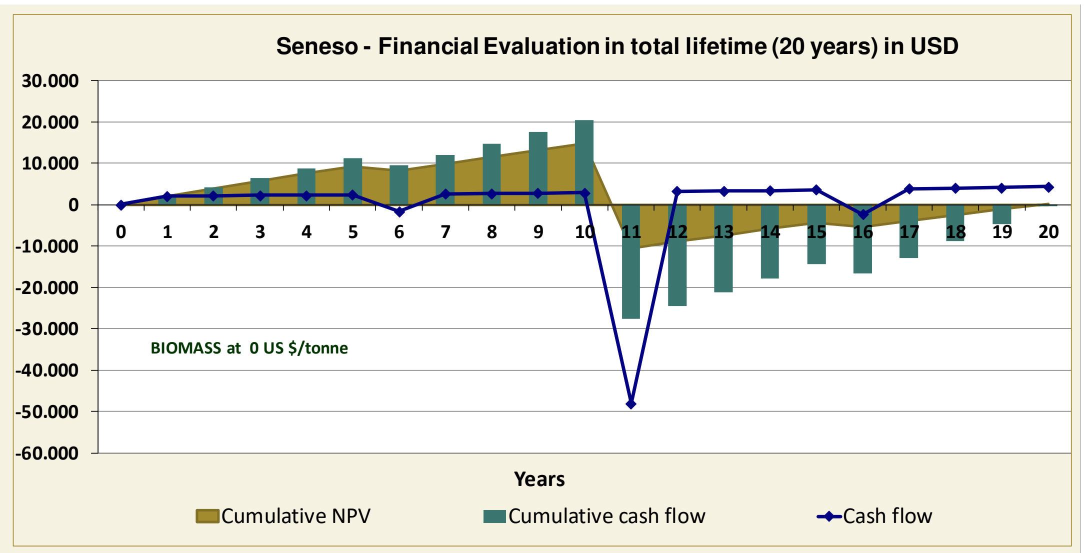
Figure 24. Distribution mini-grid outline for Seneso.

6.4.4 Financial Assessment Results

The financial results for Seneso Community, which has the highest feasibility score, are shown in Figures 25, 26 and 27. In Seneso, the field work revealed that on average, households spend close to GHS 50.00 (approx. US$ 12.5) worth of electrical energy services in a month (on lighting with candles, kerosene lamps or torches, and mobile phone charging.

Figure 25 shows that if the initial investment costs are entirely subsidized, the minimum tariff that would balance the replacement and M&O&M costs would be 8.8 US$ cents/kWh, equivalent to an average payment per user of about 4.3 US$ per month.

Biomass is assumed to be available at no cost in Figure 25. If biomass was priced at US$ 5 per tonne (due to eventual costs of collection and transportation to the gasification power plant), then the minimum tariff would be US$ cents 9.5 per kWh (average payment of US$ 4.7 per month). If biomass was priced at US$ 10 per tonne, then the minimum tariff would be US$ cents 10 per kWh (average payment of US$ 5 per month).

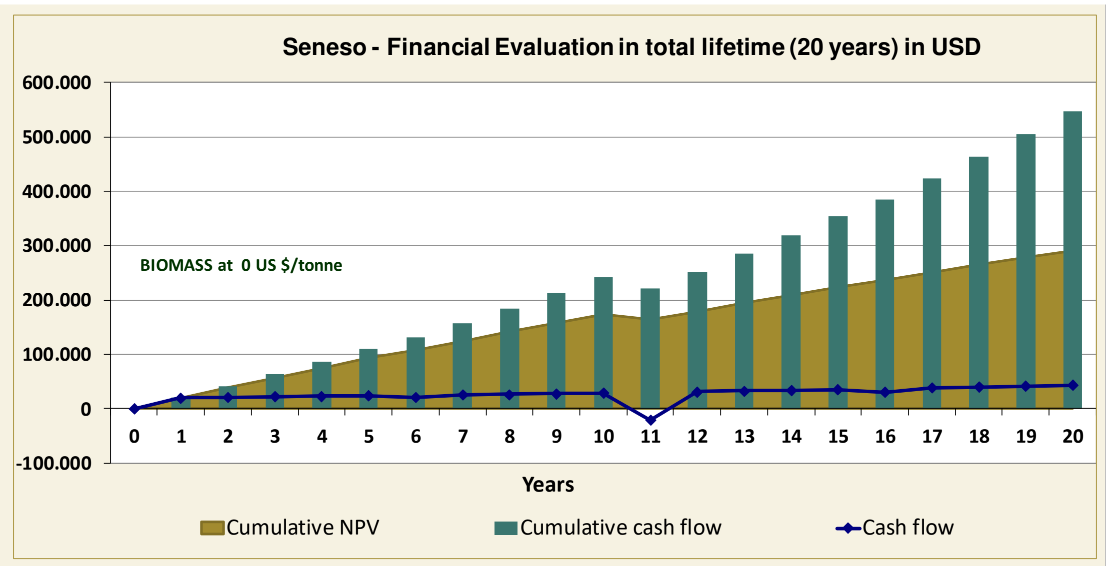


Case a) LEVEL OF SUBSIDY ON CAPEX: 100% **reference HH tariff:** 0,088 **USD/kWh**

NPV 151 **USD Sustainable Project** **average payment:** 4,34 **USD/month**

Figure 25: Financial analysis of a 24-7 electricity service in the community of Seneso under a 100% subsidy funding scheme, with biomass supplied at no cost, using minimum tariff for financial viability

If the current average household electricity expenditure were charged to customers, profitability of the business would be enhanced, as shown in Figure 26, with all other conditions set to those in Figure 25.



Case b) LEVEL OF SUBSIDY ON CAPEX: 100% **reference HH tariff:** 0,254 **USD/kWh**

NPV 291.543 **USD Sustainable Project** **average payment:** 12,50 **USD/month**

Figure 26: Financial analysis of a 24-7 electricity service in the community of Seneso under a 100% subsidy funding scheme, with biomass supplied at no cost, using tariff equivalent to current average expenditure.

The case of private funding has also been modelled, under the assumption that a 15% minimum return on equity would be expected by investors over a 20-year project lifetime period. Figure 27 shows the minimum tariff that would need to be charged to users to reach IRR profitability levels of 15% and 25% for several shares of private co-funding. Figure 27 also shows that by applying a customer tariff equivalent to the current expenditure on electricity equivalent uses in Seneso (US$ 12.5 per month), a subsidy of about 35% on initial investment would enable a profitability of 15%. In order to reach a profitability of 25%, an investment subsidy of 60% would be required.

It can also be concluded from Figure 27 that by applying national uniform tariffs (End User Tariff (EUT)) [8], which as of January 2017 were set at about US$ cents 17.7 per kWh (including service charge), 65% of the investment costs would need to be subsidized to enable a 15% profitability, with the remaining 35% coming from private co-funding.

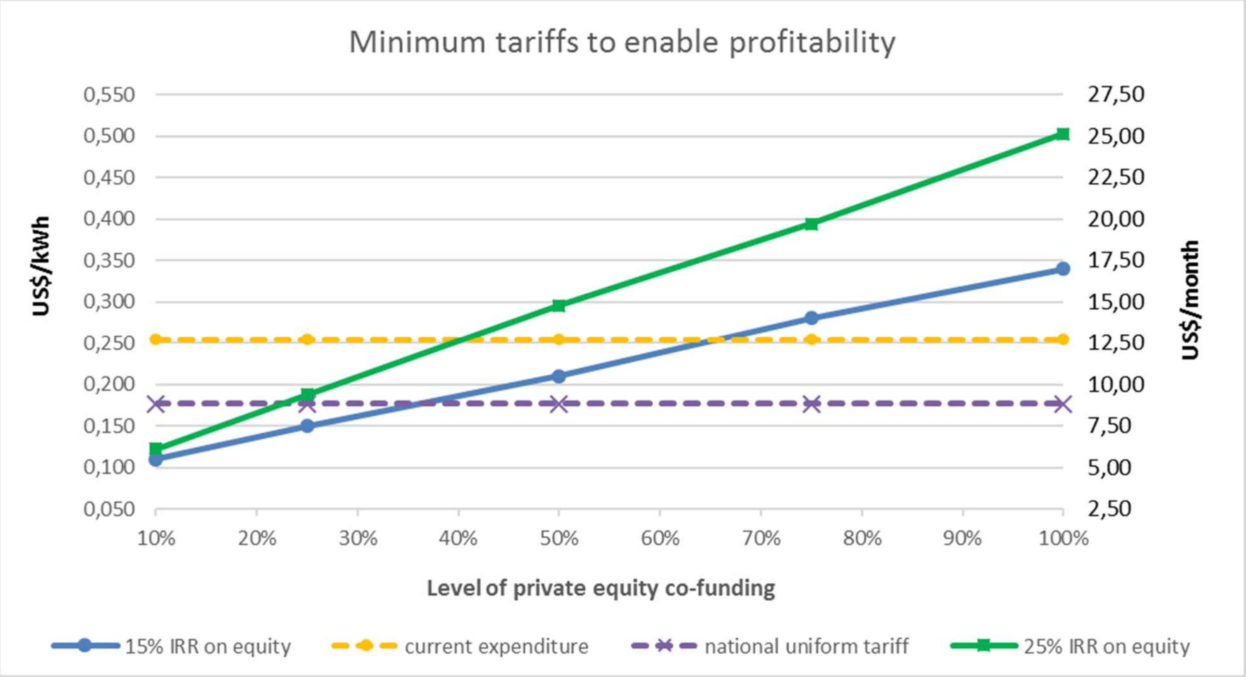


Figure 27: Financial analysis of a 24-7 electricity service in the community of Seneso under several levels of private co-funding.

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[8] Available from the Ghana Public Utilities Regulatory Commission, http://www.purc.com.gh/purc/node/177

6.5 APPENDICES

6.5.1 Appendix 1 – Minigrid Load factor

Table A: Load factor calculation (community of Seneso, under scenario 2 operation)

		Load profile Seneso (scenario 2)																								**average daily load factor** (weighted average)
	Time	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
	power (kW)	11	6.6	6.6	6.6	6.6	6.8	4.5	9.1	9.1	9.1	9.1	9.1	11.1	11	11	11.1	11.1	8.8	14.6	33.3	33.2	31.3	23	13	
minigrid supply from CHP unit 1		-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	11.1	11.1	8.8	14.6	16.6	16.6	15.6	11.5	-	
load factor CHP unit 1	*peak load supply 17kW*										-	-	-	-	-	65%	65%	65%	52%	86%	98%	98%	92%	68%		76.4%
minigrid supply from CHP unit 2				-	-	-	-	-	-	-	-	9.1	9.1	11.1	11	-	-	-	-	-	16.6	16.6	15.6	11.5	13	
load factor CHP unit 2	*peak load supply 17kW*										-	53%	53%	65%	65%						98%	98%	92%	68%	77%	74.3%
minigrid supply from inverter (batteries)		11	6.6	6.6	6.6	6.6	6.8	4.5	9.1	9.1	9.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
load factor inverter	*peak load supply 10-12kW*	91%	66%	66%	66%	66%	68%	45%	91%	91%	91%															74.1%
																										74.9%

6.5.2 Appendix 2 – Electricity demand projection

Table B. Reference daily electricity demand estimation for the Very Low (VL) HH demand segment:

household	Type of consumption		Power demand per unit (W)	Units	Hours	Energy demand (kWh/day)	Energy demand (kWh/month)	%
Very Low consumption **(<20kWh/month)**	1	Lamps	10	3	6	0.18	**5.48**	**53%**
	2	Radio	20	1	7	0.14	**4.26**	**41%**
	3	Music Center (-DVD player)	25	0	0	0		
	4	Colour TV	60	0		0		
	5	Cell phones charger	10	2	1	0.02	**0.61**	**6%**
	6	Fan	50	0		0		
	7	Refrigerator	900 Wh/day	0	0	0		
	8	Iron	1000	0	0	0		
	9	Hair cut equipment/ Clipper		0	0	0		
	10	Freezer	1kWh/day	0	0	0		
	11	Water pumps	100	0	0	0		
	12	Computer	250	0	0	0		
TOTAL VL						**0.34**	**10.34**	**100%**

Table C. Reference daily electricity demand estimation for the Low (L) HH demand segment:

household	Type of consumption		Power demand per unit (W)	Units	Hours	Energy demand (kWh/day)	Energy demand (kWh/month)	%
Low consumption **(>20 kWh/month and <50 kWh/month)**	1	Lamps	10	5	6	0.3	**9.13**	**26%**
	2	Radio	20	1	8	0.16	**4.87**	**14%**
	3	Music Center (-DVD player)	25	1	3	0.075	**2.28**	**6%**
	4	Colour TV	60	1	5	0.3	**9.13**	**26%**
	5	Cell phones charger	10	2	1	0.02	**0.61**	**2%**
	6	Fan	50	1	6	0.3	**9.13**	**26%**
	7	Refrigerator	900 Wh/day	-	24	0		
	8	Iron	1000	0		0		
	9	Hair cut equipment/ Clipper				0		
	10	Freezer	1kWh/day	-	24	0		
	11	Water pumps	100	0	1	0		
	12	Computer	250	0	1	0		
TOTAL L						**1.15**	**35.14**	**100%**

Table D. Reference daily electricity demand estimation for the Medium (M) HH demand segment:

household	Type of consumption		Power demand per unit (W)	Units	Hours	Energy demand (kWh/day)	Energy demand (kWh/month)	%
Medium consumption **(>50 kWh/month and <100 kWh/month)**	1	Lamps	10	7	5	0.35	**10.65**	**14%**
	2	Radio	20	2	3	0.132	**4.02**	**5%**
	3	Music Center (-DVD player)	25	1	2	0.05	**1.52**	**2%**
	4	Colour TV	60	1	4	0.24	**7.30**	**10%**
	5	Cell phones charger	10	2	1	0.02	**0.61**	**1%**
	6	Fan	50	1	6	0.275	**8.37**	**11%**
	7	Refrigerator	900 Wh/day	-	24	0.9	**27.38**	**36%**
	8	Iron	1000	1	0.5	0.5	**15.21**	**20%**
	9	Hair cut equipment/ Clipper				0		
	10	Freezer	1kWh/day	-	24	0		
	11	Water pumps	100	0	1	0		
	12	Computer	250	0	1	0		
TOTAL M						**2.57**	**75.05**	**100%**

Table E. Reference daily electricity demand estimation for the High (H) HH demand segment:

household	Type of consumption		Power demand per unit (W)	Units	Hours	Energy demand (kWh/day)	Energy demand (kWh/month)	%
High consumption **(>100kWh/month)**	1	Lamps	10	8	5	0.4	**12.17**	**12%**
	2	Radio	20	2	3	0.12	**3.65**	**4%**
	3	Music Center (-DVD player)	25	1	2	0,05	**1.52**	**1%**
	4	Colour TV	60	1	4	0.24	**7.30**	**7%**
	5	Cell phones charger	10	3	1	0.03	**0,91**	**1%**
	6	Fan	50	2	6	0.6	**18.25**	**18%**
	7	Refrigerator	900 Wh/day	1	24	0.9	**27.38**	**27%**
	8	Iron	1000	1	1	1	**30.42**	**30%**
	9	Hair cut equipment/ Clipper				0		
	10	Freezer	1kWh/day			0		
	11	Water pumps	100			0		
	12	Computer	250			0		
TOTAL H						**3.44**	**101.60**	**100%**

Table F - Residential demand - Seneso, Baseline scenario

HH segment	count	% households per segment	Total consumption (kWh/day)	Total consumption (kWh/month)
VL	10	17%	3.29	100
L	35	63%	40.27	1,225
M	8	15%	19.72	600
H	3	5%	9.86	300
Total	**56**	**100%**	**73.14**	**2,225**

Table G. Residential demand - Seneso, Scenario 2 (includes a population and a socio-economic growth factor)

HH segment	count	% households per segment	Total consumption (kWh/day)	Total consumption (kWh/month)
VL	10	10%	3.29	100
L	29	30%	33.37	1,015
M	39	40%	96.15	2,925
H	19	20%	62.46	1,900
Total	**97**	**100%**	**195.27**	**5,940**

Table H. Community activities demand – Seneso, Scenario 2

Community demand	Electricity Consumption kWh/month	%
Public lighting	1639.64	79.24%
Church	0	0%
School	386.53	18.66%
Health center	43.56	2.11%
Total	**2069.73**	**100.00%**

Table I. Commercial activities demand – Seneso, Scenario 2

Commercial demand	Electricity Consumption kWh/month	%
Dressmaking	66.19	17.75%
Mechanics	0.00	0.00%
Minishops	97.28	26.08%
Drinking bars	126,95	34.84%
Barbers	5.11	1.37%
Hairdressing salons	4.02	1.08%
Music /TV center	69.11	18.53%
Bakeries	1.34	0.36%
Total	**370.1**	**100.00%**

Table J. Commercial activities demand – Seneso, Scenario 2

Industrial demands	Electricity Consumption kWh/month	%
Agro processing	909.73	94.74%
Cold storage	46.48	4.84%
Other productive	4.02	0.42%
Total	**960.23**	**100,00%**

6.5.3 Appendix 3 – Calculation of Electricity production from biomass

Table K. Estimated energy content (MJ) in crop residue

Type of Residue	Seneso	Boniafo	Bompa	Jaman	Nakpaye
Maize stalk	3.036.168	4.637.946	1.644.792	1.202.420	714.244
Maize cob	1.104.425	1.687.082	598.303	437.388	259.811
Maize husks	1.181.201	1.804.362	639.895	467.793	277.872
Beans Straw	618.474	25.335	304.934	361.300	317.528
Beans shells	207.823	8.513	102.466	121.406	106.698
Groundnut straws	777.629	693.811	516.957	329.816	222.020
Groundnut shells	170.593	152.206	113.408	72.354	48.706
Rice straw	49.867	156.381	1.849.141	89.505	298.327
Rice husk	6.962	21.834	258.179	12.497	41.653
Cassava stalks	82.110	499.145	110.348	347.390	353.137
Millet straw	-	-	12.225	93.678	104.277
Guinea Corn straw	-	-	-	-	35.624
Yam Straw	94.796	431.939	1.100.944	2.363.136	447.184
TOTAL	**7.330.049**	**10.118.553**	**7.251.591**	**5.898.684**	**3.227.078**

Table L. Estimated power generation with a gasifier and gas engine powerplant

Type of Residue	Seneso	Boniafo	Bompa	Jaman	Nakpaye
Maize stalk	134.941	206.131	73.102	53.441	31.744
Maize cob	49.086	74.981	26.591	19.439	11.547
Maize husks	52.498	80.194	28.440	20.791	12.350
Beans Straw	27.488	1.126	13.553	16.058	14.112
Beans shells	9.237	378	4.554	5.396	4.742
Groundnut straws	34.561	30.836	22.976	14.659	9.868
Groundnut shells	7.582	6.765	5.040	3.216	2.165
Rice straw	2.216	6.950	82.184	3.978	13.259
Rice husk	309	970	11.475	555	1.851
Cassava stalks	3.649	22.184	4.904	15.440	15.695
Millet straw	-	-	543	4.163	4.635
Guinea Corn straw	-	-	-	-	1.583
Yam Straw	4.213	19.197	48.931	105.028	19.875
TOTAL kWh/year	**325.780**	**449.713**	**322.293**	**262.164**	**143.426**
Total kWh per month	27.148	37.476	26.858	21.847	11.952
Maize residues only	19.710	30.109	10.678	7.806	4.637

7 CONCLUSIONS AND ASPECTS FOR FURTHER RESEARCH

The potential for electricity generation from biomass residues available in rural districts in Ghana has been investigated in this research by developing a planning framework and applying it to investigate three representative energy supply schemes:

(i) Decentralised Power Generation from clustered Smallholder and Irrigation farms

(ii) Trigeneration (power, heating and cooling)

(iii) Mini-grid electricity service for off-grid communities

7.1 INTEGRATED PLANNING METHODOLOGY

While technology for electricity production from agricultural biomass residues is progressing, managing decentralised rural electricity programmes or projects is still a challenge in many developing countries, including Ghana, given the variety and complexity of the factors that condition biomass to energy supply chains. Such complexity has been previously formulated in academic exercises, but with limited practical applicability for energy provision planners, practitioners and potential investors.

This research has put effort in deploying a holistic approach to sustainable biomass-to-energy planning, yet flexible to adapt to different regulatory scenarios and energy supply configurations. A qualitative framework has been developed to characterise the planning of decentralised power generation and subsequent service schemes based on agricultural biomass residues. The framework follows an iterative approach, emphasizing the necessity of starting the planning of programmes and projects by determining a need or an interest for the energy service and how stakeholders desire to use the service. It takes into consideration four critical components: social development component, organisational/institutional component, technical component, and financial component, with their respective metrics.

The framework has been applied to three real case study configurations in Ghana, involving primary data collection via field surveys, sustainability modelling and discussion of the results with policy makers and practitioners in Ghana. In the three cases, the application of the framework has enabled the structuration of the analysis, the quantification of metrics and the achievement of conclusive results about the conditions for techno-economic feasibility of biomass-to-energy projects.

Moreover, some aspects of this methodology are being taken into account by stakeholders in Ghana within the formulation of rural electrification policies and regulations (minigrids), and the prospects of trigeneration and biomass minigrids (described in sections 5 and 6) have also triggered the interest of international and Ghanaian private funders in conducting detailed due diligence appraisals of project investments.

7.2 DECENTRALISED POWER GENERATION

The planning methodology developed has been applied to analyse the case of power generation from crop residues from small farms and irrigated rice projects in rural districts in Ghana. The technical analysis has shown that there is indeed potential to use these resources to generate electricity to be fed into the national grid. The financial analysis shows that a 1000 kWe plant using clustered residue from small holder farms and irrigation projects would not be profitable under current FiT rates unless additional income from the use of residual heat can be mobilised. Either higher FiT (about 25% more on the current rates) or a minimum level of subsidy of 30% on initial investment costs of the plant will be needed to achieve minimum profitability rates above 12% IRR.

Consideration of carbon credit sales could improve the financial situation but then again, even at the most optimistic price of carbon, profitability is still dependent on a slight increase in FiT rates and / or a little capital subsidy. The government of Ghana is aiming to achieve universal access to electricity by 2030. Due to the challenges of extending grid to remote agrarian communities, biomass electricity plants could be considered and piloted as one of the technological solutions. With about 3 million people living in remote and sometimes grid-inaccessible communities, exploring biomass electricity technologies, and where appropriate hybrid technologies combining biomass with solar and wind could be a solution worth exploring. Including biomass technologies in hybrid systems could reduce the need for storage systems in rural mini-grids and eventually reduce the cost of mini-grids for rural electrification.

7.3 TRIGENERATION FROM SMALLHOLDER FARM RESIDUES

The potential for cogeneration and even trigeneration from clustered agricultural residue in the small holder farms studied in Ghana is high. Uncertainties that currently hinder investment in biomass-to-energy projects (biomass calorific value, appropriate technology, cost and sustainability of the equipment, yield of the global generation system) have been assessed by using the integrated planning methodology developed in the early stages of this research.

Techno-economic results show that 600 kW and 1 MW CHCP plants run on local agro residue to generate power, heating (for cassava or maize drying) and cooling (to refrigerate tomatoes) are feasible in certain rural districts, considering a minimum 20% yearly profit for investors' equity.

Crop residue biomass could generate additional income for farmers in the range of 29 to 64 US $/tonne of crop residue if a minimum of 60% of the heat produced can be traded.

The consideration of carbon financing under the most common prices currently traded in existing carbon funds has little impact on the preliminary project results; however, if more favourable schemes (like the Swedish carbon tax) are considered, the viability of cogeneration and trigeneration plants run on agro residue can be possible even with a low level of residual heat sales.

7.4 RURAL ELECTRIFICATION: MINIGRID SERVICE BASED ON BIOMASS

The planning methodology has been used to build a simulation model of standalone mini-grid electricity service in rural communities in Ghana based on their own agricultural residues. This configuration has a large replication potential in SubSaharan Africa.

The model is focused on five Ghanaian farming communities, and takes into consideration the four key components that integrate the planning methodology proposed in this research: socio-economic, technical, organizational and financial. The technical analysis shows that the potential electricity generation from biomass residues available within the communities compares favourably with their projected demand under three electricity consumption scenarios (baseline, demographic growth and increase of productive uses of electricity).

As with most biomass electricity analysis, it is not profitable from the perspective of an entrepreneur with 100% private funding; however, by applying a customer tariff equal to the current expenditure on electricity equivalent uses in the communities, a subsidy of about 35% on initial investment would enable a private investor profitability of 15%, whereas a 60% subsidy could enable a profitability of 25%. Applying the national electricity uniform tariff would require a 65% of the investment subsidies to enable a 15% profitability, with the remaining 35% coming from private co-funding. The case studies were conducted in previous MFP communities because of their experience in operating and maintaining a small electricity generator. Moreover, we do not envisage much difficulty in transferring these case studies to communities that have not been involved in MFPs. However, more sensitisation and further training would be required in such communities. Past studies in Ghana indicate that most agricultural residues are openly burnt after harvest, in order to prepare for the next planting season. Burning agricultural residue has pollution effects for the immediate farmer neighbourhoods. While gasification will generate other forms of waste that has to be managed, collecting the residues from farmer fields after harvest will help address the smoke pollution problems associated with open combustion of the residues, and help create a healthier environment. Biomass based electricity systems are expected to play a crucial role in the electrification of remote rural communities where agricultural residues are abundant.

7.5 RECOMMENDATIONS FOR FURTHER RESEARCH

The research presented in this Thesis contributes to informed and inclusive decision-making in the development of biomass-based power generation and electricity service solutions for rural areas in Ghana. Since this is certainly a continuous learning field, the following aspects for further research can be recommended at this stage.

In terms of the planning methodology, it would be interesting to consider the development of a software format to facilitate its systematic application and enable a widespread usage within the biomass energy planning and practitioner community. For instance, a GIS interface could help in assessing biomass feedstocks locations and fast track the techno-financial feasibility results. Another possibility could be to work on the visual presentation of the results, to enable a quick elaboration of programme or project key performance indicators. Such development could well fit into multilateral funders' project preparation procedures, like the World Bank Project Concept Note (PCN), Project Appraisal Documents (PAD) and Implementation Status Reports (ISR), or the GEF Project Preparation Grants (PPG). In any case, a software evolution of the methodology could be considered as a profit-making proposition, to complement (or even compete with) existing commercial tools such as HOMER or others.

Regarding the technological front, an aspect of further research can be the consideration of solar photovoltaic (PV) generation to complement the biomass plants, especially in those locations with dry season periods that can hinder the availability of agricultural residues. Another possibility is the widening of the biomass feedstock types considered, by also assessing animal waste and their energy conversion by means of digestion technologies and biogas production as a complement to solid agricultural residues usage.

As per the specific case studies analysed in this research, further financial scenarios can be modelled (e.g. shorter project lifetimes, higher or lower investor expectations on equity returns, or the inclusion of further direct and indirect social valorisation parameters such as the mid and long term benefits of employing local unskilled labour) to suit the specificities of funding actors or project developers.

Finally, regarding the social and organizational components, extended investigations to other countries in West Africa or to the whole Sub Saharan African region would provide a wider scope of socio-economic contexts and potential management or business models, and would therefore help to enhance the understanding of opportunities to deploy biomass-to-energy solutions at a larger scale.

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