FEASIBILITY STUDY OF BIOMASS HYBRID MICRO-PLANTS FOR MINI-GRID BASED ELECTRICITY SERVICES IN RURAL COMMUNITIES IN GHANA

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ABSTRACT: Electricity access is key in driving socio economic development. Since Ghana initiated its National Electrification Scheme (NES) 20 years ago, access has risen to 72%, with over 88,000 communities yet to be electrified. From 2006 to 2008, the Multifunctional Platform (MFP) programme provided mechanical energy services based on diesel engines in 38 off-grid communities; yet these communities are rich in agricultural residues. International experience has shown that decentralised power generation by biomass gasification systems is cost competitive for remote villages with low load demand, and has the lowest environmental impact as compared to other conversion technologies. Additionally, the Ghanaian Renewable Energy Law sets forth the possibility for distribution utilities to benefit from renewable energy obligations in investments conducted in rural areas. This study was commissioned to investigate the prospects of electricity service provision based on biomass gasification technology. To this end, the feasibility of using agricultural residues to run a 24 hour mini-grid electricity service has been characterised in five MFP communities in Ghana (Brong Ahafo and Northern regions). The institutions involved in this study, TEC-KNUST, KITE and IS.UPC are partners in the diffusion of sustainable energy solutions, as a key action to eradicate energy poverty in the region.

Keywords: Rural development, Electricity, Small scale application, Gasification, Agricultural residues, International cooperation, Feasibility studies.

1 INTRODUCTION: ELECTRICITY IN GHANA

Access to energy is crucial to human welfare; no residential, commercial or industrial activity can be conceived without energy supply. Current dependence on fossil fuels (Oil, Natural Gas, Coal) is being progressively contested by society, academia and to some extent policy makers due to the increasing scarcity of fossil fuel reserves (implying price rises and 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. Undoubtedly, today's biggest scourge in electricity supply is the large number of people in the world who still do not have access to electricity services; The United Nations Development Programme (UNDP) and the International Energy Agency (IEA) estimate that one fifth of the world's population currently lacks access to such services, with 1.4 billion people having no access to electricity [1] [2].

Table I. Electricity access in the world Regional aggregates [1]

	People without electricity millions	**Electrification rates** Global %	Urban %	Rural %
Africa	**587**	**41.9**	**68.9**	**25.0**
North	*2*	*99.0*	*99.6*	*98.4*
Sub-Saharan	*585*	*30.5*	*59.9*	*14.3*
Developing Asia	**799**	**78.1**	**93.9**	**68.8**
China & East Asia	*186*	*90.8*	*96.4*	*86.5*
South Asia	*612*	*62.2*	*89.1*	*51.2*
Developing countries	**1,438**	**73.0**	**90.7**	**60.2**
World	**1,441**	**78.9**	**93.6**	**65.1**

In the current context of reviewing the MDG fulfilment status [3], the situation in Sub-Saharan Africa is poignant: on average, 2 out of 3 families, mainly in rural areas, live without electricity or access to modern energy services, in what experts have come to address as the "Hidden Energy Crisis" [4].

It is clear that many of the world's poorest will never be reached, in their life time, through centralized national electricity infrastructures alone if the 'business as usual' approach to energy planning continues. At the same time, decentralised renewable energy based solutions have proofed to be the only viable option for users with low or very low energy demands, who live in remote or isolated areas. In this context, electricity generation form biomass has been gaining interest and institutional support worldwide, and particularly in Sub Saharan Africa [5].

For the specific case of Ghana, the Government of Ghana (GoG) intends achieving universal access to electricity by 2020 [6]. With barely six years to go, about 30% of the Ghanaian populace are still without access to electricity. While the electrification rate reaches 85% in urban areas, in rural areas is about 23% [7]. The majority of those without access are located in remote areas and island communities' where extending the national grid is difficult and costly.

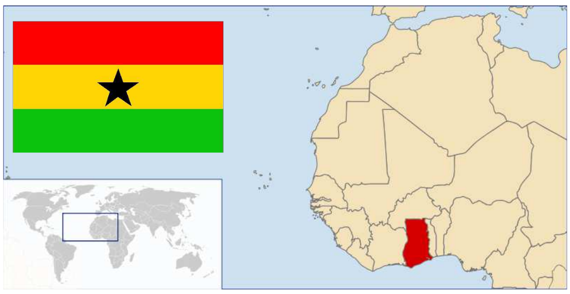

Figure 1: Ghana in West Africa

2 TARGET COMMUNITIES

From 2006 to 2008, KITE implemented the Multifunctional Platform (MFP) program funded by UNDP to provide mechanical energy services in 38 off-grid communities in the Brong Ahafo and Northern regions of Ghana. These MFPs consist of a diesel lister engine mounted on a chassis to produce mechanical power to drive agro processing equipment.

The MFP enterprises are usually affected by high and volatile crude oil prices, which add to their operational cost thereby rendering them financially unsustainable. Also, in the process of providing mechanical energy for agro processing, these MFP diesel engines emit greenhouse gases (GHGs) which have negative impacts on the environment. Although these MFPs have met the mechanical energy needs of inhabitants of the communities, they do not produce electrical energy which is also needed in the communities.

Reducing poverty and creating an enabling environment for socio-economic development in rural areas have engrossed successive governments in Ghana and, for that matter, the Ghana government has set an ambitious target of universal access to electricity by 2020. Among the efforts being made to achieve these goals include the introduction of the National Electrification Scheme (NES), which was launched in 1989 to extend the national electricity grid to all communities throughout the country with population of 500 or more by 2020. Since the inception of NES, electricity access has risen to 72% with over 88,000 communities yet to be electrified. The Self Help Electrification Project was in addition introduced to help speed up the process by electrifying towns and villages which were prepared to help themselves by contributing to the cost of electrification of their communities. However, the community should be located within 20km of an existing 33kV or 11kV source of supply.

While some of the MFP communities have been connected to the national grid, a sizeable number of them do not even feature in the National Electrification Master Plan. Most of these communities are situated over 30 km away from the national grid and that makes their grid-based electrification not economical. Yet these communities need to have access to modern electrical energy services in one form or another. Meanwhile, most of such rural communities produce biomass and agricultural residues that are enough to meet all their electricity demands by using biomass based power plants. Through this system of power generation, apart from providing the rural communities self-sufficient energy, it can also generate employment and development opportunities to the rural inhabitants.

Previous experience in other countries have shown that decentralized power generation by biomass gasification systems can be cost competitive, in terms of life cycle cost analysis, for remote villages with comparatively low load demand. Moreover, research has shown that biomass gasification is the biomass conversion to electricity technology that poses the lowest environmental impact [8].

It is in light of this that the Kumasi Institute of Technology, Energy and Environment (KITE) in partnership with the Universitat Politècnica de Catalunya (UPC) of Barcelona in Spain and The Energy Centre – Kwame Nkrumah University of Science and Technology (TEC-KNUST) in Ghana is implementing a project partly funded by ECREEE to study the feasibility of small scale biomass gasification mini grids for electricity services in five off-grid MFP communities in Ghana.

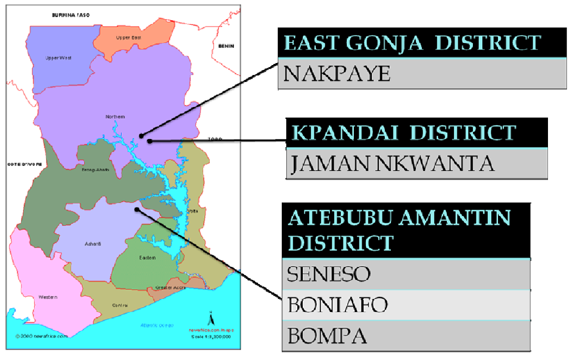

Figure 2: The five Ghanaian rural communities that have participated in this project.

3 OBJECTIVES OF THIS STUDY

The overall objective of the study is to contribute to sustainable development in West Africa by providing detailed know-how on the prospects of small scale electricity generation and services schemes based on biomass gasification technology for mini grids. This is to investigate how the effective utilization of local agro waste can be used to provide electricity using a biomass gasification system in five MFP communities in the Brong Ahafo and Northern regions of Ghana.

The specific objectives of the study include the following:

- To define the general socio-economic character of the communities, including local community resource management structures and practices;
- Assess the biomass resource capacity of the communities
- To estimate the current as well as potential electrical energy requirements for economic and domestic purposes in the study area; and
- To assess the feasibility of using the biomass resources in the 5 target communities to provide

4 METHODOLOGY

This research has consisted in desk studies, primary data collection in field visits (May and November 2013), laboratory analysis in Ghana and in IS.UPCs pilot gasification plant in Spain, and the integrated feasibility assessment for each of the communities.

The main tasks undertaken have been:

A. Desk review and inception:
   - a.1 Feasibility analysis methodology adaptation (components, quantified criteria, protocols)
   - a.2 Desk review of available information

B. Field work:
   - b.1 Preparation of field work: materials, logistics
   - b.2 Field visits to 5 MFP communities

C. Feasibility characterisation and community ranking:
   - c.1 Socio-economic component analysis (needs assessment, energy demand, income structures, prospects for business development)

c.2 Technical and technological component analysis (supply chains, biomass resources, batteries, distribution mini-grid, possibilities for cogeneration and trigeneration, local provider capacities)

c.3 Regulatory and institutional component analysis (definition of roles and responsibilities, adaptation of existing standards, protocols)

c.4 Financial component analysis (Cost-benefit analysis, business plans, cash-flow projections, private NPV, social NPV)

c.5 Integration of all components into feasibility matrix and characterisation of all assessed communities

c.6 Ranking of communities potentials and selection for detailed implementation preparation

Table I. Field interviews summary (May-November'13)

Community	Population	No. of households	Households interviewed	Farmers interviewed
Seneso	528	52	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**	**309**	**120**	**89**

Figure 3: Meeting with citizens from the community of Seneso during the field work in May 2013.

5 RESULTS AND DISCUSSION

5.1 Electricity Demand Assessment

Load Categories

The estimation of current as well as future demand has been based in the differentiation of 4 main load categories: Residential, Institutional, Commercial and Industrial.

i. **Residential Consumptions**: Include private households (HHs) where energy is consumed primarily for lighting and as input for the provision of services (including room conditioning, refrigeration, entertainment/communication, etc.) from a range of electricity consuming appliances such as radios, sound systems, refrigerators, fans, etc. Residential consumptions have been segmented further into 4 consumption classes defined primarily by the consumption profile of residential customers in a similar but electrified community.

Very Low (VL): HHs consuming up to 20kWh/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 50kWh/month. Households in this category are expected to use fan and/or TV in addition to the previous (VL) load.
Medium (M): HHs consuming between 50 and 100kWh/month. Households in this category are expected to add small refrigerators in addition to the load (L).
High (H): Households consuming more than 100kWh/month.

ii. **Institutional Consumptions**: represent the consumptions of public institutions in the community. Public lighting, public water pumping, energy use in churches, 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.

iii. **Commercial Consumptions**: represent 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.

iv. **Industrial Consumptions**: represent the potential electricity to be consumed by light industrial concerns identified in the field surveys such as the MFP operation. The consumption depends on the operational cycle of the concerned industry.

The estimated electricity demand for each category is then aggregated (summed up) to give the projected total energy consumption for the first year of the planning period (assumed to be 2014). In determining how the yearly consumption and peak demand will evolve year by year over the projected planning period, three scenarios were considered.

Definition of scenarios

Baseline Scenario: This scenario estimates the potential electricity consumption in the 5 communities were the community to have access to electricity at the moment based on current energy consumption patterns of the reference community, Nyamoase.

Scenario 1: Considers the evolution of yearly consumption and peak demand over the period 2014-2024 occasioned by population growth. 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 more lamps and in most cases computers) and the demand for more public lighting as the population grows.

Scenario 2: Projects the evolution of yearly consumption and peak demand over the planning period (2014-2024) as results of population growth and a 20% socio-economic growth to be experienced in the communities attributed largely 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, 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 in communities without any in the baseline scenario).

General assumptions made

A reference potential tariff for mini-grid schemes has been considered at 0.35GH¢/kWh per month; (doubling the residential tariff for customers within the 51-300 kWh band). Using the reference tariff for mini-grids and the Willingness to Pay revealed by electricity consumers in Nyamoase, a reference maximum monthly expenditure for the various categories of customers and their distribution were estimated as shown in Tables II and III.

Table II: Reference maximum monthly expenditure for baseline and scenario 1

Demand profile baseline & scenario 1	Reference max. expenditure	% of households
VL	3.14 GHC/month	11%
L	7.84 GHC/month	33%
M	31.45 GHC/month	46%
H	more than M	10%

Table III: Reference maximum monthly expenditure for Scenario 2

Demand profile Scenario 2	Reference max. expenditure	% of households
VL	3.14 GHC/month	9%
L	7.84 GHC/month	28%
M	31.45 GHC/month	41%
H	more than M	22%

Table II indicates that a sum of 90% of potential customers consuming up to 100 kWh/month (VL, L and M categories) will be willing to incur maximum expenditures of between GH¢3.14 and GH¢31.45 each month on electricity compared to an expenditure greater than GH¢31.45, which is incurred by the remaining 10.54% consuming over 100 kWh/month in the Baseline Scenario and Scenario 1. In scenario 2 (Table III), households will evolve from their respective categories to the nearest demand categories due to increase in energy consumption. As a result the potential customers consuming up to 100 kWh/month are expected to decline to 78% incurring maximum expenditures of between GH¢ 3.14 and GH¢ 31.45 while households consuming above 100 kWh will increase to 22%.

The daily load profiles have been defined by a percentage distribution of energy consumed in hourly periods for the different categories: household lighting, powering household equipment for each household demand level (VL, L, M, H), public lighting, school, church, health centre, commercial, farming, fishing and alcohol distillation.

Electricity for heating purposes (cooking, ironing, baking, and distillation of alcohol) is not considered given its extremely low efficiency on mini-grids and the possibility to use alternative renewable systems (solar thermal systems or biomass systems) much more cost-effectively.

As for public lighting, each house will have an outdoor light used for security lighting and will be on from 7pm till 5am during the whole year. The exact number of light poles cannot be estimated, given that it will depend on exact layout of the lines and the distribution of the houses in the villages. As a preliminary reference, in dense household nuclei, 1 pole for every 2 houses is used. However, the detailed layout of public lighting must be considered for a final sizing of the energy demand. Low consumption High Pressure Sodium (HPS) lamps are considered, with power reduction control (2 power levels).

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

Electricity demand SENESO community		Baseline Scenario	Scenario 1 population growth	Scenario 2 Scenario 1 + economic growth
Residential	HHs VL (<20kWh)	31	64	51
	HHs L (<50kWh)	321	675	585
	HHs M (<100kWh)	1283	2700	2417
	HHs H (>100kWh)	443	932	1935
	Total	2077	4372	4989
Institutional kWh/month		1643	1947	2069
Commercial kWh/month		53	53	373
Industrial kWh/month		467	467	958
Total kWh/month		4241	6839	8390
Total kWh/day		139	225	276
Peak power demand kW		14	26	29

Table V: Demand forecast for the five communities

	Electricity (kWh/month)			Power peak (kW)		
	b-line	Sc. 1	Sc 2	b-line	Sc 1	Sc 2
Seneso	4241	6839	8390	14.2	25.6	28.9
Boniafo	3479	5668	7312	12.8	22.6	25.6
Bompa	5482	9732	11667	21.3	40.6	46.1
Jaman Nkwanta	5228	8944	10509	19.0	35.9	40.8
Nakpaye	2966	4125	5531	8.5	13.7	15.6

Finally, the load profiles have also been defined in order to approach the sizing of the micro power plant and mini grid in each community. The figure below shows the profiles for Seneso:

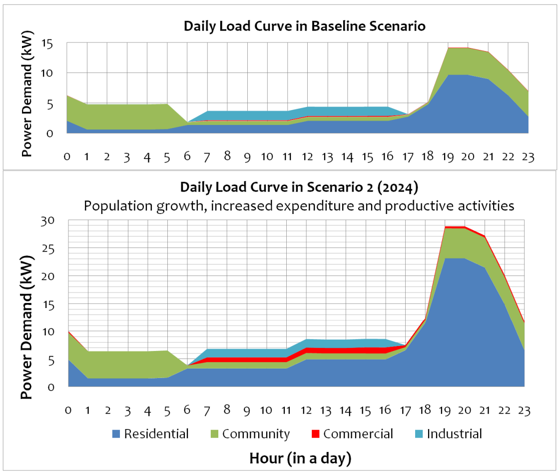

Figure 4: Load profiles in the community of Seneso.

5.2 Biomass Waste Assessment

Based on the data collected in the field work, the overall quantities of crop residue that could be available have been estimated. The quantities of crop residue depend on the output of farm crops, and therefore, on the sown areas of farm crops. It is noted that in practice, not all the existing crop residues can be collected and used for bioenergy production due to technical constraints, ecosystem functions, and other uses (e.g. animal fodder, fertilizer, domestic heating and cooking). Clearly, collection of all the residues could adversely affect soil fertility [9]. Currently, many of the crop residues are scarcely utilized. Estimation of the amount of crop residue available is done using the residue to product ratio. Residue to Product Ratio (RPR) is simply the ratio, by mass, of a crop's residue to the actual product. An RPR of 1 means the amount of residue of the particular crop equals the amount of product obtained from the same crop. The residue-to-product ratios (RPRs) of the various crops vary depending on various factors including crop variety, water and nutrient supply, yield of crops, moisture content at time of measurement, and the use of chemical growth regulators. Some of these factors depend on climatic conditions and the level of management.

Reference values on RPR in Ghana were obtained by previous studies from TEC-KNUST. Field measurements were conducted on farmer fields to determine RPRs of the various crops. The following procedure was used for the farmer field measurements:

a) Four plots each of size 20m by 20m square was obtained by random sampling from each of the farms visited.
b) The residue to product ratio (RPR) of the various residues was determined using the weight of the product and residues obtained from the plants.
c) An average RPR was determined for each farm from the different plots.
d) An average RPR was derived for the various locations.

The biomass resource assessment conducted in the communities established that between 211 and 586 metric tonnes of agricultural residues are generated in the communities annually, which can be converted to electricity using a biomass gasification technology. Table VI shows the annual quantity of agricultural residues generated in each community

Table VI. Monthly crop residue production in each target community

Residue	Seneso	Boniafo	Bompa	Jaman Nkwanta	Nakpaye
Maize stalk	12.861	19.646	6.967	5.093	3.025
Maize cob	4.286	6.548	2.322	1.698	1.008
Maize husks		7.858	2.787	2.037	1.210
Beans straw	5.144	153	1.847	2.189	1.924
Beans shells	999	41	493	584	513
Groundnut straws	3.318	2.960	2.205	1.407	947
Groundnut shells	734	655	488	311	210
Rice straw	240	754	8.913	431	1.438
Rice husk	40	126	1.485	72	240
Cassava stalks	352	2.139	473	1.488	1.513
Yam straw	670	3.053	7.782	16.704	3.161
Millet straw	-	-	59	453	504
Guinea corn straw	-	-	-	-	157
Total (kg/month)	**28.644**	**43.933**	**35.821**	**32.467**	**15.850**

Using the calorific content for each type of biomass listed in Table VII (data from TEC-KNUST), and a reference efficiency conversion factor of 18% to electricity using a downdraft fixed bed gasifier coupled to an Otto engine gas generator set [10, 11, 12, 13, 14], Table VIII shows the potential electrical energy obtainable from crop residues at each target community.

Table VII. Calorific values of the crop residue types identified in the target communities

Residue	LHV (MJ/kg)	Residue	LHV (MJ/kg)
Maize stalk	18.15	Rice straw	17.42
Maize cob	17.49	Rice husk	14.99
Maize husks	18.10	Cassava stalks	17.99
Beans straw	15.96	Yam straw	16.04
Beans shells	12.38	Millet straw	17.12
Groundnut straws	17.58	Guinea corn straw	18.15
Groundnut shells	15.87		

Table VIII: Potential electrical energy from crop residue in each target community

Community	Potential Electrical Energy (kWh)	
	All Crops	Maize
Seneso	21,352	13,451
Boniafo	27,639	20,451
Bompa	26,474	9,495
Jaman Nkwanta	18,776	8,561
Nakpaye	11,646	4,121

Finally, the projected demand values (Table IV) are compared with the potential electricity generation figures from Table VII:

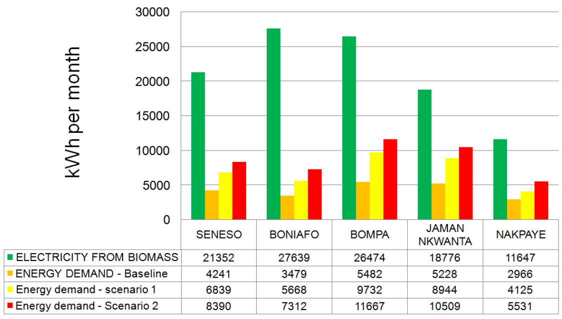

Figure 5: Summary of the electricity generation potential from crop residues compared to the electricity demand in each target community

5.3 Feasibility benchmarking

In order to rank the communities as being feasible to accept the implementation such technologies, an evaluation methodology was developed to assign score to the communities based on the criteria under consideration. Weights were given to each criterion depending on its position on the priority scale.

The tables below show the criteria used and the score assigned under different conditions.

Table IX Criteria for the feasibility weighted scoring

Scoring values		**Criterion: Community topology** weight: 20%
1	low	dispersed HHs interdistances > 100, overall radius > 2km; distance to grid < 5km
2	medium	clustered HHs interdistances < 100 m, overall radius < 2km; distance to grid < 5km
3	high	clustered HHs, interdistances < 50 m, overall radius < 1km; distance to the grid > 5km
4	very high	clustered HHs, interdistances < 30 m, overall radius < 500m; distance to the grid > 5km
Scoring values		**Criterion: Current energy use and expenditure** weight: 20% *(*) 1USD = 2 GHS November 2013*
1	low	av. expenditure < 10 GHS/month (*) No community uses, No productive uses
2	medium	av. expenditure < 20 GHS/month No community uses, No productive uses
3	high	av. expenditure > 20 GHS/month No community uses, No productive uses
4	very high	av. expenditure > 40 GHS/month Community & Productive uses, Experience with electricity
Scoring values		**Criterion: Potential generation from biomass waste** weight: 40%
1	low	< 10% electricity demand worst case scenario
2	medium	> 30 % electricity demand w.c.s
3	high	> 70% electricity demand w.c.s
4	very high	> 90% electricity demand w.c.s
Scoring values		**Criterion: Management model prospects** weight: 20%
1	low	community not organised no basic M&O nor ADM capacity
2	medium	some organisation no basic O&M nor ADM capacity
3	high	some organisation, basic ADM capacity or basic O&M capacity
4	very high	community well organised, basic O&M capacity and basic ADM capacity

Table X Overall Feasibility Rating

Overall Score	Feasibility Rating
Above 3.5	Very high
Between 3 and 3.4	High
Between 2 and 2.9	Medium
Below 1.9	Low

Table XI: Feasibility results

	Seneso	Boniafo	Bompa	Jaman Nkwanta	Nakpaye
Community topology	4	2	4	4	2
Current energy use and expenditure	3	2	3	3	3
Potential generation from biomass waste	4	4	3	2	3
Management model prospects	4	2	2	2	2
Overall (weighted) rating	3,8	2,8	3,0	2,6	2,6
Feasibility score:	**very high**	**medium**	**high**	**medium**	**medium**

5.4 Preliminary financial analysis

A financial spreadsheet model has been built to assess the cash flow over an operational life time of 20 years in the community of Seneso, which has the highest feasibility score. The discount rate has been taken as 6% and the inflation rate as 4%.

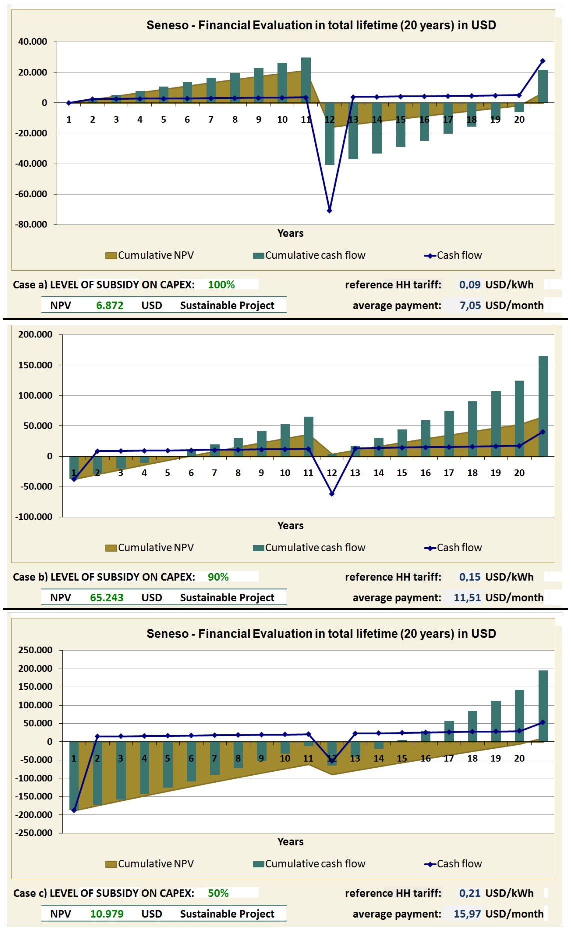

Figure 6: Preliminary financial analysis of a 24-7 electricity service over 20 years in the community of Seneso under different levels of subsidy on initial investment costs: a) 100% subsidy, b) 90% subsidy and 10% private funds, c) 50subsidy and 50 equity funds.

Note that the average monthly payment is indicated ij Figure 6, and can be compared with the figures in Tables II and III to assess the affordability of the service. In Seneso, the field work revealed that in total, households spend close to GhȻ 30.00 (approx. 0.15USD) worth of electrical energy services in a month.

As main conclusions, this study has shown that:

- **A quality electricity service** (24h-7d) based on local crop residue **is feasible** in the 5 target communities assessed (very high feasibility in one community, high feasibility in another one, and medium feasibility in te remaining three)
- In one of the communities, Seneso, **the financial evaluation is positive even without 100% subsidies** on initial investment costs.

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8 AUTHORS ORGANISATIONS