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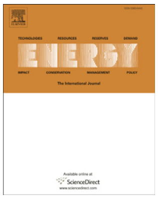

Mini-grid electricity service based on local agricultural residues: Feasibility study in rural Ghana

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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, decentralized biomass mini-grids can be a reliable electricity supply solution. This study investigated the technical and financial feasibility of decentralized electrification based on agricultural waste gasification in five Ghanaian communities. Results show that the projected electricity demand of the communities compares favorably 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%.

1. Introduction

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 newly 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*' [1]. Per the targets, Goal 7 directly supports the implementation of the "Sustainable Energy for All (SEforAll)' agenda launched by the United Nations Secretary General, which has been embraced by many developing countries [2].

The broad aim of these initiatives, on the electricity side, is to reach the 1.3 billion people that still live without electricity, most of them in rural areas of Asia and sub-Saharan Africa. For many countries in these regions, the main barrier to universal electricity access is supply to rural areas which are not connected to the electricity grid [3]; [4,5]. Sub-Saharan Africa has more people living without access to electricity than any other world region – more than 620 million people, and nearly half of the global total [6]. 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

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around 100 million people [7]. 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% [8].

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, to ensure universal access to electricity in the country by 2020. Ghana has also subscribed to the SEforALL agenda and was the first country to prepare an SEforALL Action Plan [2]. Ghana's SEforALL Action Plan aims to continue the drive for rural electrification and promote productive uses of electricity [9]. Currently, about 15% of the population (an estimated 4 million people), living in sparsely populated rural communities, remain unconnected to electricity [8]. 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 [10]. According to Sánchez et al. [11]; 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.

In view of this, the Government of Ghana is targeting the construction of 55 renewable energy-based mini-grids by 2020 [12], 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 [12]. In 2016, five pilot mini-grids were commissioned in island communities, but these are all solar and solar-wind hybrid based technologies, with diesel genset backup [13]. 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 [14]. 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 [15], can also generate employment and other development opportunities for the rural inhabitants, through the productive use programme being targeted by the national SEforALL programme.

In most Ghanaian rural communities and indeed in most places in sub-Saharan Africa, agricultural residue biomass is an abundant resource that can be supplied on a regular basis. According to Sánchez et al. [11]; 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 [16–19], regional and district levels [20,21], agro-industrial level [22–24]; [25], or clusters of agricultural residue to supply biomass to larger scale power plants [14]. The only community level study that we have sighted, modelled biogas production systems for a rural community [26]. 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 [27–29]. It has been asserted by Ekinci [30] 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 [31]. 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 [32]. 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 to reduce the risk is not adequate. 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.

The aim of this study, therefore, is to use primary data obtained at the community level to investigate the technical and financial feasibility of agricultural waste gasification based decentralized electricity generation. The specific objectives of the 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.

Biomass based electricity systems are expected to play a crucial role in the electrification of remote rural communities where agricultural residues are abundant [33]. In this context, we expect our paper to contribute to the literature with some of the key issues surrounding these systems within a developing country context.

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., [5,34–41]). Different types of technologies for converting biomass into useful energy have been studied and ongoing research continue to explore these issues. Zabaniotou et al. [42] studied the performance of gasification systems with internal combustion engine on different agricultural wastes and found that different biomass types had different effects on gasification parameters and process efficiency. A similar study by Leu [43] explored small-scale solid biomass power systems based on direct coupling of an updraft fixed bed gasifier with a Stirling engine. Andrew et al. [44] 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. [45] 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 [46], as well as other related resources [47]. 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 [48].

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 [33,49]. Pantaleo et al. [50] 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 [51] also investigated the cost of raw fuel collection and processing costs, transportation costs, electricity prices, prices of agricultural products, price level of agricultural waste, 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.

3. Material and methods

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) [52] 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 Fig. 1).

3.2. Study approach

3.2.1. 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 1.

3.2.2. 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

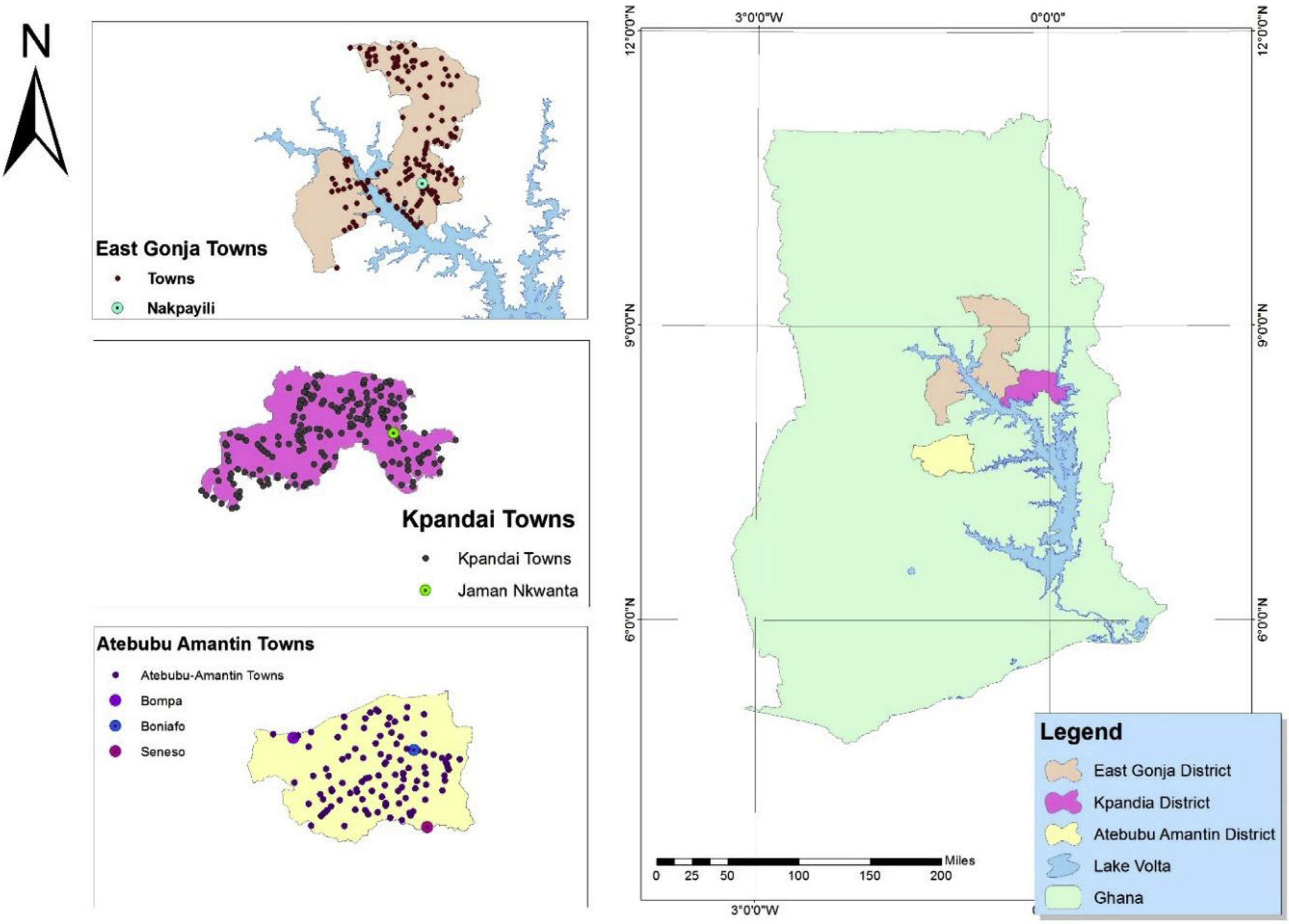

Fig. 1. The five Ghanaian rural communities that participated in this study.

Table 1
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	3257	313	120	89

mini-grid electrification. Factors considered in the analysis were socio-economic factors, technical and technological factors, and financial factors.

3.3. Data collection and analysis

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 [53] and [54]: 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 [13].

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 were considered: Baseline Scenario, Alternative Scenario 1 and Alternative Scenario 2.

- 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 [13], 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 [55]. 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) [15]. 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.

3.3.2. 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 [56]. 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 [57]. Reference values on residue to product ratios (RPR) were obtained from previous studies in Ghana [20,26] to estimate crop residue availability. Lower Heating Values (LHV) for energy potential estimation were obtained from Arranz-Piera et al. [14]; Kemausuor [58]; Thomsen et al. [59]; Duku et al. [16]; Jekayinfa and Scholz [60].

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 waste.

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 100 kW) solid biomass to electricity conversion technology [19]; [61]. 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 [62]; [63]. Recent studies on small scale gasification experiences in rural Africa [64] 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 [33]. 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.

3.3.3. *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 2 shows the assumptions made in conducting the financial analysis [13,64,65].

4. Results and discussion

4.1. *Biomass resource availability and electricity generation*

The annual quantity of agricultural residues generated in each community is presented in Table 3, 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 [62,63]. Considering the LHV stated in Table 3, and a biomass to electricity conversion efficiency of 16% (adaptation from Ref. [63]; 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 4 (additional calculations are provided in Appendix 3). Maize residues dominate electricity generation potential, ranging from 35 to 74% of the total electricity potential.

4.2. *Electricity demand projections*

Electricity demand projections were made using data obtained from the community survey, as well as demand segmentation observed from pilot mini-grids in the country; Table 5 shows the demand segmentation patterns being observed at the Ghana Ministry of Energy piloted mini-grids [13]; [66], and the corresponding categorisation under the energy availability quality factors developed by the U.S. National Renewable Energy Laboratory [67]. Table 5 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 [13,66]. Detailed demand data for the Seneso community is shown in Table 6 and Appendix 2. Summary for all the five communities is shown in Table 7. Load profiles have been defined to ensure correct sizing of the micro power plant and mini-grid in each community. Fig. 2 shows load profiles for Seneso Community for the Baseline in 2017 and Scenario 2 in 2027. 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 [68]. Residential demand dominates, also typical of the national picture [68].

Table 2
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)	2400	US$/kW
Battery bank (lead-acid, OPzS)	90	US$/kWh
Bi-directional inverter, monitoring system and protections	720	US$/kW
Distribution lines (cabling low voltage, single phase)	3930	US$/km US$/km
Public lighting (poles and LED fixtures)	7800	US$/kW
Engineering and construction management cost	880	Unit
Powerhouse construction	15,000	US$/kW
Installation and training works	530	US$/kW
Logistics	725	
Replacement costs	31%	Over initial investment costs
Batteries and gasifier parts at year 10, CHP engines overhauling every 5 years, and corresponding transport costs		
Staff cost (Management, Operation)	5500	US$/year
Maintenance (spare parts) cost	2200	US$/year
Total M&O&M	7700	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	

Table 3
Annual crop residue production in each target community.

Type of Residue	Estimated Crop Residue (kg) per year					[a]Assumed moisture content (%, wet basis)	Lower Heating Value (MJ/kg) [14, 39]
	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	2046	24,631	29,184	25,648	16.45	12.38
Beans shells	13,322	546	6568	7782	6840	16.45	15.60
Groundnut straws	44,234	39,466	29,406	18,761	12,629	18.86	17.58
Groundnut shells	9786	8731	6506	4151	2794	13.82	17.43
Rice straw	3205	10,050	118,839	5752	19,173	15.50	15.56
Rice husk	534	1675	19,807	959	3195	13.01	13.04
Cassava stalks	4692	28,523	6306	19,851	20,179	20.00	17.50
Millet straw	–	–	788	6040	6723	63.57	15.51
Guinea Corn straw	–	–	–	–	2096	61.80	17.00
Yam Straw	8935	40,711	103,765	222,727	42,147	15.00	10.61
TOTAL (kg)	**431,891**	**585,781**	**477,633**	**432,918**	**211,346**		

[a] Values obtained **from** experiments conducted in Ghana and elsewhere by [14]; [16,58–60].

Table 4
Potential electricity generation from crop residue in each target community.

Community	Monthly Electricity yields (kWh/month)[a]	
	All crops	Maize only
Seneso	27,148	19,710
Boniafo	37,476	30,109
Bompa	26,858	10,678
Jaman Nkwanta	21,847	7806
Nakpaye	11,952	4637

[a] efficiency conversion factor (biomass to electricity) of 16% (adaptation from Ref. [63] based on information from commercial plants developed by HUSK Power Systems Pvt. Ltd. in India, Uganda and Tanzania).

Fig. 3 shows electricity demand values compared with the potential electricity generation from the biomass resources available within the communities (Table 4). 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.

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 8. 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 8). 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 9, 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.

Finally, the engineering outline of the mini-grids was carried

Table 5
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 6
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**

Table 7
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	12,972	21.2	40.4	53.4
Jaman Nkwanta	5174	8822	11,683	18.9	35.8	47.3
Nakpaye	2938	4076	6147	8.4	13.5	18.1

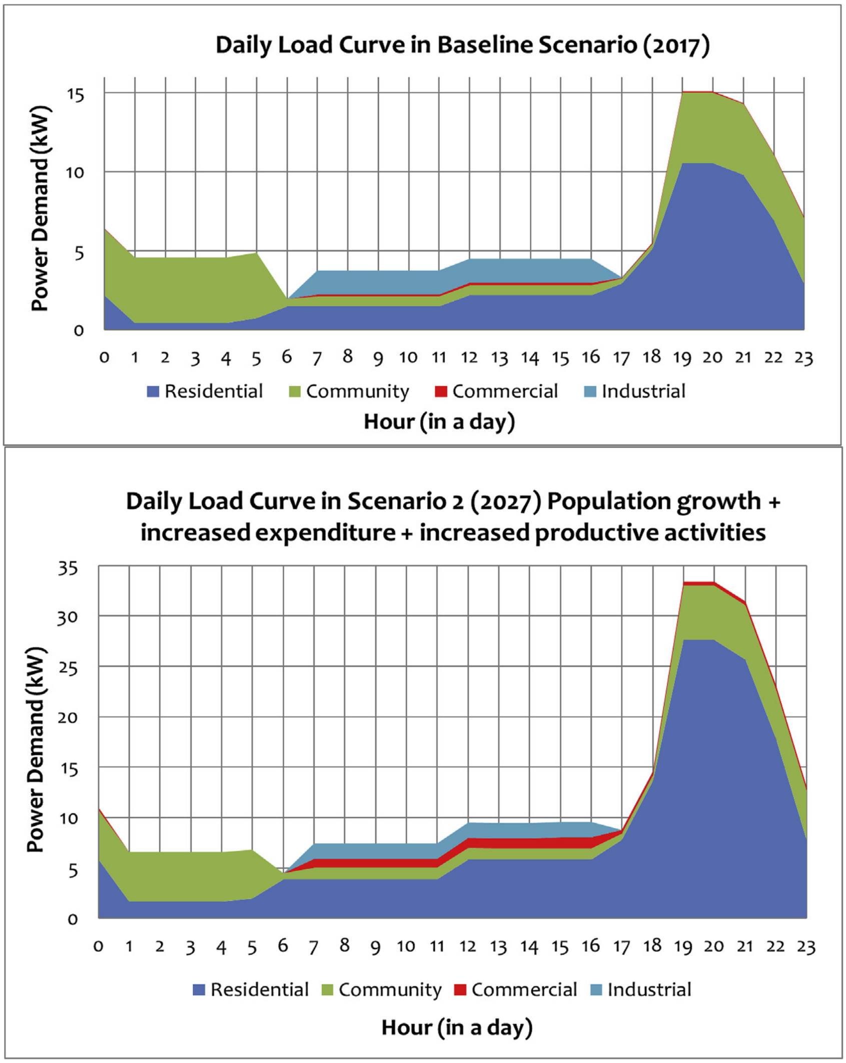

Fig. 2. Projected load profiles for the Seneso Community: Baseline Scenario (top), Scenario 2 (bottom).

out, considering a hybrid biomass syngas genset supply architecture (with batteries), as described in Fig. 4. Tables 10 and 11 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 also shown in Fig. 5.

4.4. Financial assessment results

The financial results for Seneso Community, which has the highest feasibility score, are shown in Figs. 6–8. 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.

Fig. 6 shows that if the initial investment costs are subsidized entirely, 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 Fig. 6. 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

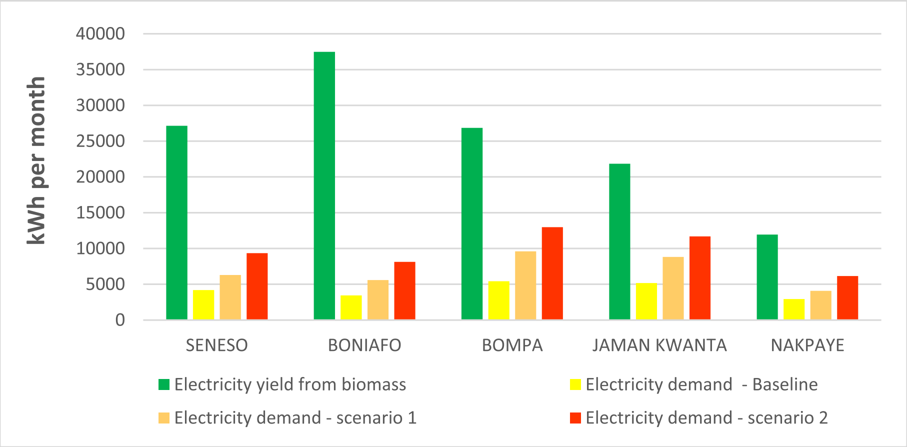

Fig. 3. Summary of the electricity generation potential from crop residues compared to the electricity demand in each target community.

Table 8
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 < 5 km
2	medium	clustered HHs: interdistance < 100 m, overall radius < 2 km; distance to grid < 5 km
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 > 5 km
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 waste. 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 $^{\text{organisation,}}$ basic Administration capacity or basic O&M capacity
4	very high	Community well organised, basic O&M capacity and basic Administration capacity

Table 9
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 waste	4	4	3	2	3
Management $^{\text{model}}$ 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

payment of US$ 5 per month).

If the current average household electricity expenditure were charged to customers, profitability of the business would be enhanced, as shown in Fig. 7, with all other conditions set to those in Fig. 6.

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. Fig. 8 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. Fig. 8 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 Fig. 8 that by applying national uniform tariffs (End User Tariff (EUT)),[1] 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.

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

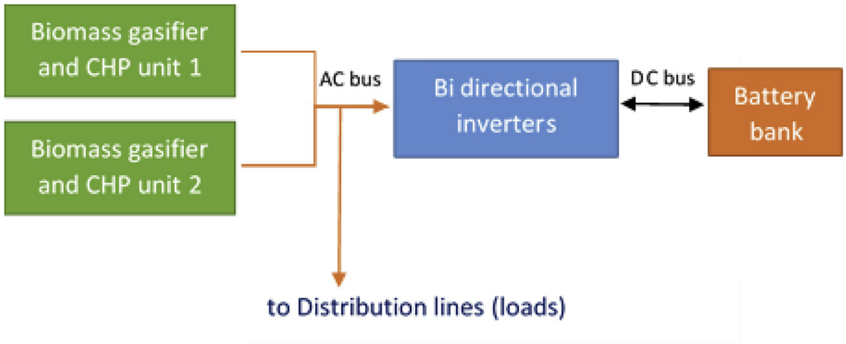

Fig. 4. Block diagram of biomass hybrid generation architecture.

Table 10
General Operating conditions used to model the mini-grid case for Seneso.

Electricity service supply	307 kWh per day. Availability: 24 h a day, 7 days a week
Powerhouse gross active electric power	34 kW in AC (50 Hz)
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 h per day (reported by manufacturers), at 16% electrical efficiency (conservative estimation) Gasifier 1 - operating 2pm–11pm Gasifier 2 - operating 10am to 2pm, and 7pm–12pm Batteries – 0am to 10am Average daily load factor: 74.9% (Appendix 1)

Table 11
Technical specifications and CAPEX of the mini-grid case for Seneso.

Component	Value	Unit	Reference manufacturer	Reference investment cost (US$)
Biomass gasifier (downdraft) CHP plant	2 × 17	kW	HUSK POWER	81,600
Lead-acid Battery bank	90	kWh	SUNLIGHT RES OPzV	8000
Inverter (bi-directional)	2 × 5	kVA	STUDER (with a 30-min peak load supply of 12 kVA)	6400
Monitoring system	1	unit	TTA	800
Powerhouse (3 rooms) with fence	30	m^2	Local builders	15,000
Distribution lines (aerial)	1500	m	TTA	5900
Public lighting (LED)	60	poles	TTA	11,700
User connection, smart meters and indoor wiring	140	users	TTA	22,400
Installation	Based on TTA references			13,000
Logistics	Based on TTA references			24,600
Project Development	Based on TTA references			35,000
Total CAPEX US$				**224,400**

5. Conclusions

Planning rural electrification projects in developing countries can be a challenging activity for decision makers and practitioners. In this paper, we have presented a feasibility study and simulation model for the development of standalone mini-grid electricity service in rural communities in Africa using their own agricultural residues, in a case study comprising five Ghanaian farming communities which have benefited from previous MFPs and are therefore well positioned for such interventions. The study takes into consideration four key components that have been assessed: socio-economic, technical, organizational and financial. The technical analysis shows that the potential electricity generation from biomass residues available within the communities compares favorably 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 waste 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

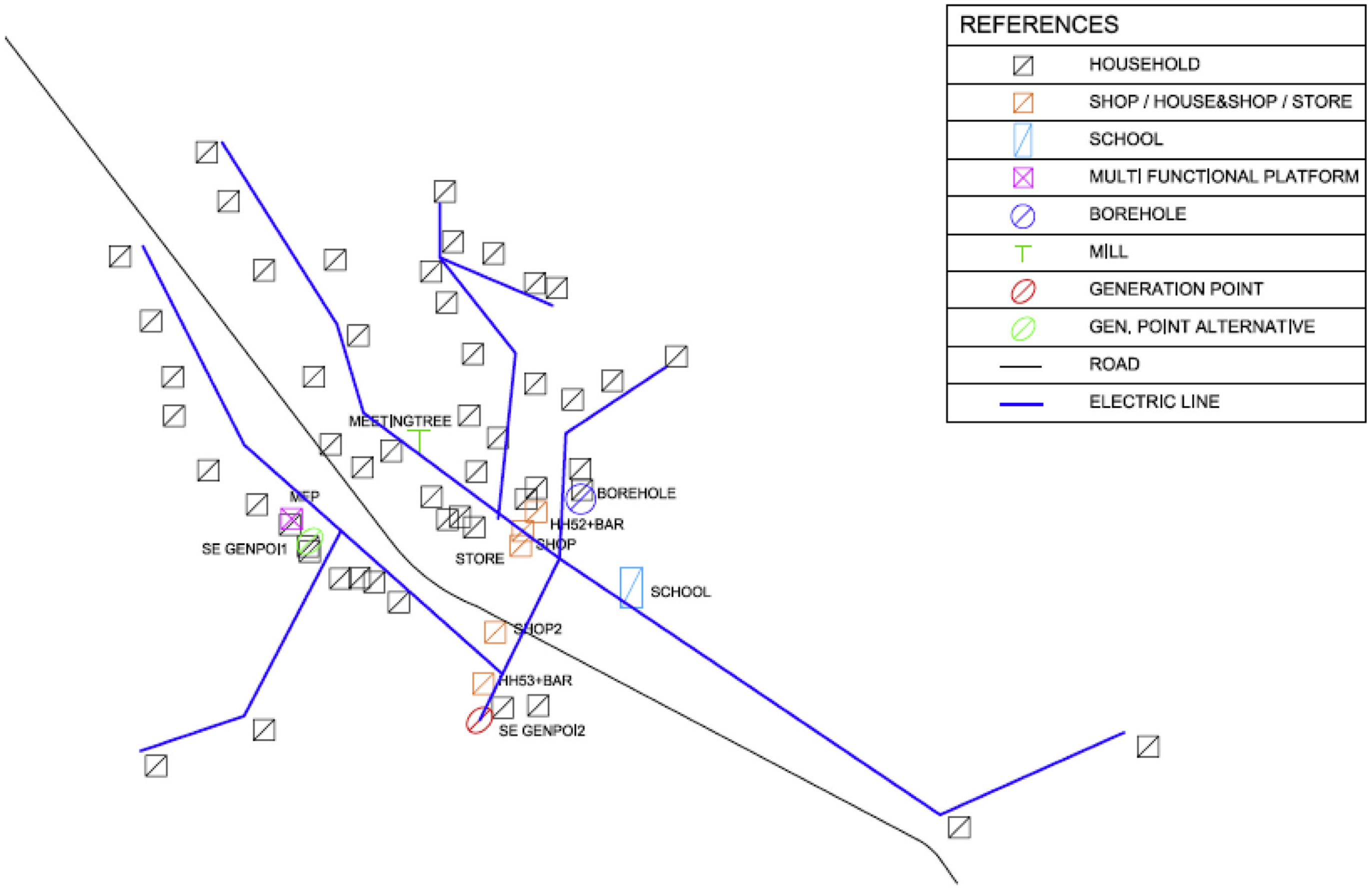

Fig. 5. Distribution mini-grid outline for Seneso.

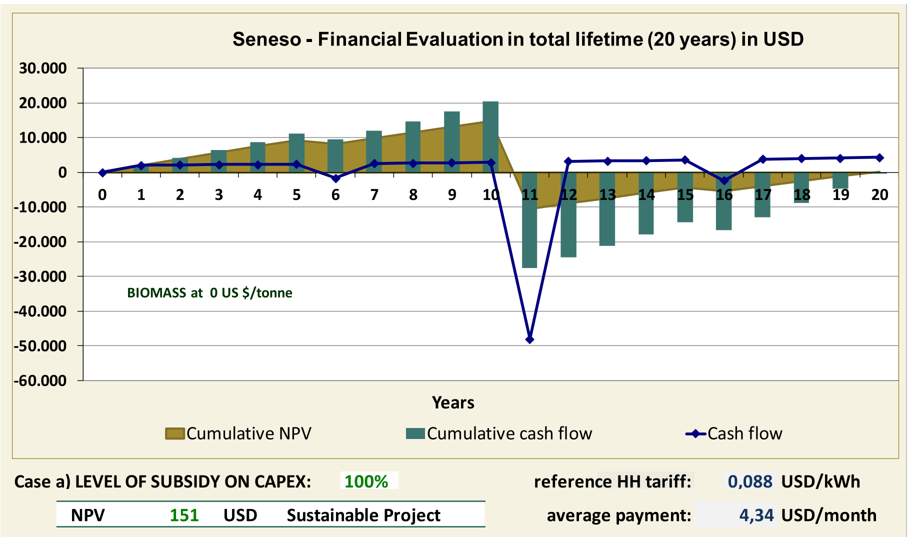

Fig. 6. Financial analysis of a 24-7 electricity service in the community of Seneso under a 100% subsidy funding scheme, with biomass supplied at no cost, using minimum tariff for financial viability.

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. In this context, we expect our paper to contribute to the literature with some of the key issues surrounding these systems within a developing country context. Another aspect of further research can be the consideration of solar photovoltaic (PV) generation to complement the biomass gasification plant.

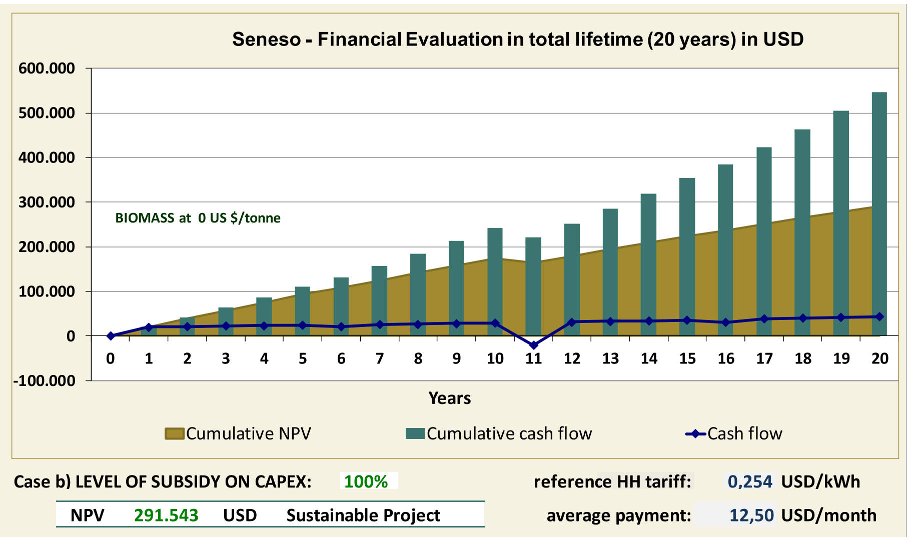

Fig. 7. Financial analysis of a 24-7 electricity service in the community of Seneso under a 100% subsidy funding scheme, with biomass supplied at no cost, using tariff equivalent to current average expenditure.

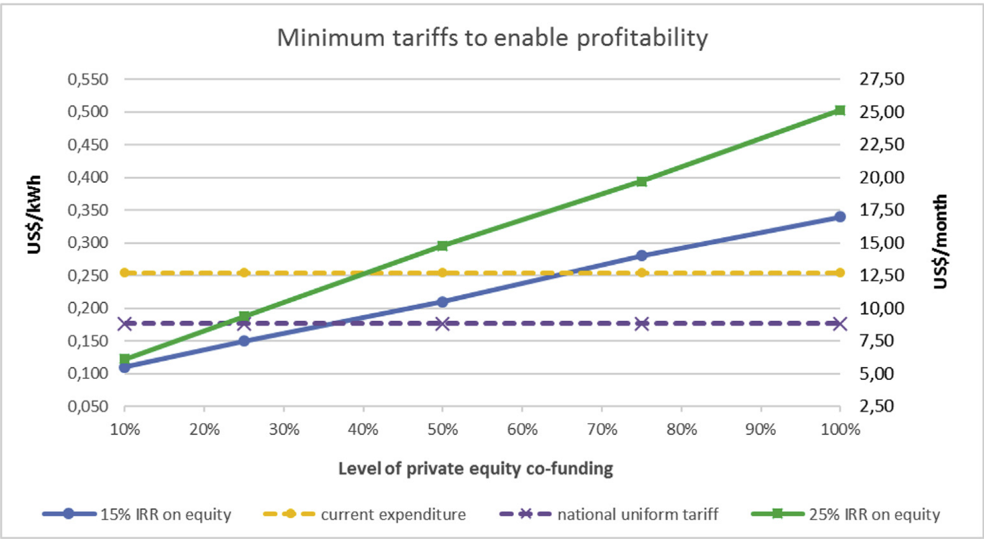

Fig. 8. Financial analysis of a 24-7 electricity service in the community of Seneso under several levels of private co-funding.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2018.04.058.

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