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Utilisation of rice residues for decentralised electricity generation in Ghana: An economic review

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Abstract: Developing countries, especially in Sub-Saharan Africa, face large challenges to achieve universal electrification. Using the case of Ghana, this study explores the role that rice residues can play to help developing countries meet their electrification needs. In Ghana, Levelised Electricity Costs (LEC) of a grid-connected 5 MWe straw combustion plant ranged between 11.6 - 13.0 UScents/kWh, based on region of implementation. Rice straw combustion is a viable grid-connected option in all regions, as the bioenergy Feed-in-Tariff is 29.5 UScents/kWh in Ghana. Residue supply cost (49-54%) contributes significantly to LEC of rice straw combustion.

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LEC of husk gasification mini-grids ranged between 5-53 UScents/kWh for rural populations between 3000-250 people. Husk gasification mini-grids can be a suitable electrification solution for these un-electrified populations, as its LEC is lower than the average LEC of grid extension (57 UScents/kWh), diesel mini-grids (102 UScents/kWh) and off-grid solar (110 UScents/kWh) systems for remote communities in Ghana. Electricity produced from husk gasification has the potential to cater to 7% of the needs of un-electrified communities in Ghana. The methodology and analysis of this study can support policymakers of similar countries decide the economic feasibility of decentralised bioenergy solutions while forming national electrification plans.

Keywords: Rice residues; electricity access; economic feasibility; rural electrification; Levelized Electricity Cost; Ghana

1 Introduction

It is well accepted that access to electricity is a key driver of economic growth, and can lead to improved education, health delivery, environmental sustainability, agricultural development and gender equality [1, 2, 3]. Despite this knowledge, 25% of the global population lives without access to electricity [3], with the Sub-Saharan African (SSA) region showing the poorest trends. While it only makes up 14% of the total population in developing countries, it accounts for 40% of the population without electricity access. The electricity access challenge in SSA has a rural-urban divide, with 89% of urban areas having access as opposed to 46% in the rural areas [4]. Furthermore, the International Energy Agency (IEA) predicts that by 2030, over 900 million people in rural areas will remain without electricity, in contrast to only 100 million in urban areas, with the vast majority being in SSA. This will result in 49% of the Sub-Saharan population still lacking electricity access by 2030 [3]. Ghana, a country in SSA has made relatively remarkable progress in electrification over the past years. However, although successive governments have implemented various policy mechanisms to increase access to electricity services [5], if electrification continues at the present rate Ghana will not be able to achieve universal electrification by 2020 as planned in their National Electricity Scheme of 1989 [6]. Similar to a number of developing countries, the major reason for the slow growth of electrification in Ghana has been the emphasis laid by the government on extending the national transmission grid. A large part of the population lives in rural areas, but less than 50% of this population in Ghana is electrified [6], with a number of villages being in remote and scattered locations [7]. This leads to a situation of 'energy isolation', with regard to grid-based electrification, where the complex geography of rural areas, long transmission lines requirements, along with low electricity demands of the diffused population makes grid extension uneconomical. The rural poor also often face economic barriers of not being able to afford connection fees, household wires and appliances [8]. Therefore, there is an increasingly widespread agreement that an integrated approach which focusses on centralised grid-based options as well as a spectrum of autonomous decentralised options should be practised in order to achieve energy access for the rural poor [8]. The modular nature of Renewable Energy (RE) resources make them well suited for decentralised systems. They provide the advantages of independence from national-level grid-based planning, limited capital requirements, and easier access to remote rural communities [2]. Further renewable resources help to lower the concerns of energy security and carbon emissions of a country, as well as promote local employment opportunities. Other than meeting electrification goals, a key driver to promote RE in Ghana is the Renewable Energy Act (2011), which seeks to promote the establishment of renewable sources in the country, and has a target of supplying 10% of the country’s electricity through renewables by 2020 [9]. However, while RE options have numerous advantages, a key factor to consider with regards to their implementation, is their economic viability. An extensive review by Kaundiya et al. on decentralised electrification systems states that several studies have conducted economic analyses of such systems in developed countries (Spain, Greece, Canada and Australia) as well as developing countries (Nigeria and India) [1]. Recently, few studies have attempted similar analyses in the SSA region, to determine the cost of decentralised systems there. Francis et al. used the Network Planner, a decision support tool to estimate the costs of different electrification technologies (grid extension, solar off-grid and off-grid diesel systems) to satisfy the needs of unelectrified populations in Ghana [3]. Adaramola et al. assessed the cost of hybrid PV-solar diesel systems for rural and semi-urban areas of northern Nigeria using the Hybrid Optimization Model for Electric Renewable (HOMER) tool [10]. Szabó et al. applied a spatial analysis for the African continent to compare the levelised costs of grid extension, mini-hydro, and off-grid solar and diesel generators [11]. A World Bank study also used spatial modelling to study the most appropriate regions in the SSA countries of Ghana, Ethiopia and Kenya for the implementation of off-grid solutions [12]. For single household systems, photovoltaic (PV) solar, wind, and diesel generators were studied, while for mini-grids wind, combined solar–wind systems, biodiesel, and diesel generators were evaluated. These studies show that there is merit in analysing the costs of decentralised electrification systems, as they are often the least-cost option for certain rural communities. However, there has been a focus on solar and diesel options, and lack of information on modern bioenergy solutions.

Modern techniques of converting biomass into energy services such as electricity and fuels have been globally recognised as a promising path to address today's growing energy challenges. This is because modern bioenergy solutions not only provide sustainable energy services, but can also promote social, agricultural and economic growth [13, 14]. Thus, the Renewable Act (2011) also considers merit in encouraging the growth of modern bioenergy solutions in Ghana [9].

Decentralised bioenergy systems such as biogas, gasification and combustion plants hare used for captive use and rural electrification in many developing countries. Shackley et al. state that rice husk gasifiers (about 50 existing plants) are extensively used in Cambodia to producepower in rice mills and ice-making factories [15]. Parnphumeesup and Kerr mention that Thailand has many decentralised bioenergy electricity plants, mainly used for industrial purposes [16]. In India, lignocellulosic material is used widely in gasifiers (1700 plants) to produce electricity in mills, sawdust industries and for rural electrification [17]. Husk Power Systems, an Indian company has installed rice husk systems for the electrification of over 300 villages in Bihar [18]. A 500 kW gasification plant was installed in one of the islands of the Sundarbans, in West Bengal in 2001, where grid extension is not feasible. This plant is still running and provides electricity to 650 consumers on this island [19].

In SSA, very few electricity producing biomass plants have been installed. Mohammed et al. mention that only one biogas plant project for electricity generation has been established in Ghana [7] and Buccholz et al. studied the performance of two woody gasifier plants that were implemented for industrial purposes in Uganda [20]. It can be observed that decentralised bioenergy has been used successfully for electricity generation in other developing regions, but there has been little implementation in SSA. Hence, this study attempts to explore the potential of decentralised grid connected and mini-grid bioenergy systems as an electrification option in SSA.

Previously, modern bioenergy was mainly generated through the fermentation of sugar and starch (cereals, grains and sugar crops) and transesterification of vegetable oils. As these methods could result in competition with food production, leading to rising food prices, food shortages and unsustainable changes in land use patterns, there has recently been an interest in the use of lignocellulosic waste for bioenergy production [21]. This process of using lignocellulosic matter such as agricultural, forestry and municipal wastes for the generation of energy is known as Second Generation production of Bioenergy (SGB). In order to avoid any threats to food prices, supply of grains to the national food basket and land use change in developing countries, only SGB technologies have been considered in our study.

Rice is an important commercial crop in Ghana, with an annual production of almost 400 million tonnes of paddy, covering a cultivation area of 162,000 hectares in 2009 [22]. Hence, agricultural wastes from rice production in the form of rice husk and straw have been shown to offer considerable potential for energy production (5.65 TJ/year) in the country [23]. According to a previous study [24] in 2012 up to 70-90% of rice residues in major rice growing regions of Ghana were openly burned or dumped in landfills and waterbodies. Thus, they were abundantly available for bioenergy production. Open burning of residues leads to the emission of harmful pollutants which pose serious environmental and health risks. Due to these concerns, many countries have imposed legislations to curb the open burning of rice fields and farmers are encouraged to seek alternative disposal methods [14].

Due to the abundant availability of rice residues in Ghana and the need to prevent unsafe disposal practises, it is worth investigating the role of rice residues as a resource for the production of bioenergy to meet the country’s electrification demands. In order to best exploit the potential of rice residue in a country, it is necessary to perform an economic feasibility assessment of SGB technologies which are best suited in the local context [25]. This is important because local conditions determine factors such as residue availability, transport conditions, electricity needs of the local population and available infrastructure for developing the power plant, which can affect the cost of electricity production.

Earlier economic studies on the use of rice residue for electricity generation include a study by Delivand et al. who carried out an economic feasibility assessment for rice straw combustion projects of various capacities to generate electricity in Thailand [25]. The effect that scaling-up of a power plant has on different financial parameters was analysed. Zhang et al. presented a methodology for estimating the cost of power generation from a rice straw combustion plant using life cycle analysis in the Jiangsu Province of China [26]. In India, Afzal et al. performed a simulation to analyse the environmental and financial profile of electricity generation from an 800 kWe rice husk gasifier [27]. Another study in India by Kapur et al. assessed the potential and economic viability of rice husk to meet the demand of parboiling, drying and milling operations in the rice processing industry through gasification [28]. Bergqvist et al. studied the economics of rice husk gasifiers, to see if these systems can meet the energy demands of the rice milling industry in the Mekong Delta of Vietnam. Bergqvist et al. also looked at the effect of Clean Development Mechanism (CDM) benefits on the economic viability of rice husk gasifiers [29]. In the SSA region, Fock et al. conducted a pre-feasibility analysis for setting up a 5 MWe rice straw combustion plant in a rice growing regions of Mali [30]. These studies all conclude that rice residue can be an economically attractive option to produce electricity. However, no previous study has compared the electrification costs of a decentralised grid-connected and stand-alone mini-grid bioenergy system using agricultural wastes in a developing country. Further, this is the first time that the economics of an agro-residue based off-grid system has been developed based on meeting the specific needs of rural communities with varying populations.

This study used the following methodology for its analysis. After choosing the best suited SGB technologies for the conversion of rice residues into bioenergy, an economic feasibility analysis of the chosen technologies was conducted. The various factors that influenced the Levelised Electricity Cost (LEC) were identified, and recommendations on how to minimise the LEC were made. As the scale of the bioenergy plant can significantly impact energy generation costs [25], the variation of the LEC of a chosen SGB technology as a function of plant size was studied for a grid-connected plant. As the off-grid plant, was intended to serve the specific needs of remote communities, the variation of plant scale was based on the size of the community. Thus the variation of LEC with community size was studied in this case. Furthermore, the LECs of chosen SGB technologies were compared with the cost of energy production from the national grid, and other mini-grid and off-grid technologies to determine if rice residue based energy production is a cost competitive option in the country. The information from this study is intended to assist policy-makers and other interested stakeholders in understanding the suitability of implementing agro-residue based electrification options in Ghana. The analysis and information in this study is also relevant and can be applied to other developing countries, to help them estimate the economic feasibility of electrification through the use of agro-residues available in their respective countries.

2 Materials and Methods

2.1 Technology Options and Sizing

Many factors such as type and availability of biomass, socio-economic conditions and end-user applications, help in determining the most suitable bioenergy conversion process for a certain region [31]. For potential implementation in Ghana, four technology pathways were initially investigated for application to rice residues. These included bio-chemical and thermo-chemical processes. The bio-chemical processes that were investigated included fermentation of rice residues for bioethanol production and Anaerobic Digestion (AD) for biogas production. These bio-chemical processes were found to be unsuitable for Ghana. AD is ideal for feeds which have a moisture content greater than 50%. However rice residues have a typical moisture content of only 10-30%. Additionally, AD requires water and animal dung for inoculum. Water is scarce in the Northern regions of Ghana and animal dung is scarce in the Central regions due to lack of cattle. Hence, no region is well suited for AD. Globally, the technology for production of ethanol from lignocellulosic feedstock is still in its initial phases of research and development, with production costs being quite high. Therefore, bioethanol form rice residues in Ghana maybe an option in the future [24]. As bio-chemical routes were ruled out, thermo-chemical options were further investigated for specific application to rice straw and husk.

2.1.1 Rice Straw

The combustion of straw has been widely used for heat and power generation in Europe and North America. Denmark has been a pioneer in straw combustion plants, and uses 52% of the wheat straw available in the country as a sole feed for the production of power [32]. Hence, the feedstock used in European power plants has primarily been wheat straw. The amount of ash produced by a feedstock and the silica and alkali content of ash mainly contribute to corrosion and fouling of a combustion system. A Danish study mentions that the ash production (15– 20%) and the amount of silica (75%) in rice straw ash is higher than that of wheat straw, which has an ash content of 5–8% and a silica content of ash as 55% (Table 1).

Table 1: Proximate composition and selected major elements of ash in rice straw, rice husk and wheat straw [33, 34]

	Rice straw	Rice husk	Wheat straw
Proximate analysis (% dry fuel)			
Fixed carbon	15.86	16.22	17.71
Volatile matter	65.47	63.52	75.27
Ash	18.67	20.26	7.02
Elemental composition of ash (%)			
SiO_2	74.67	91.42	55.32
CaO	3.01	3.21	6.14
MgO	1.75	<0.01	1.06
Na_2O	0.96	0.21	1.71
K_2O	12.3	3.71	25.6
S	0.09	0.05	0.16
Cl	0.58	0.09	0.2-0.75

However the amount of alkali in ash from rice straw is lower (15%) than wheat straw (25%) [30]. Thus, it is expected that both types of feedstock will have similar corrosion and fouling characteristics in the combustion system. Hence wheat straw combustion technology can be applied for rice straw. As straw combustion technology has been successfully established at commercial scales, is relatively simple in construction and can be used for rice straw available in Ghana, it looks promising for implementation in the country.

Grate stoker combustion is the most preferred for application in Ghana, as it is flexible to the type of feedstock used and is less sensitive to slagging and fouling [35]. While choosing the size of the combustion power plants, both security of biomass supply and economic considerations should be taken into account. Studies have shown that rice straw combustion becomes economically more favourable with increasing scales [25]. However this will be limited by the amount of rice straw available in the rice growing regions. An earlier study

[24] estimates that each rice growing region in Ghana has approximately sufficient rice straw available to satisfy the fuel needs of a 5 MWe plant (annual rice straw availability is shown in Table 2). Since this is the largest scale at which a rice straw combustion plant becomes feasible in all the rice-growing regions of Ghana, this size was chosen for the base case. We assumed that the combustion power plant is connected to the national grid.

Table 2: Annual production of rice residues in Ghana in 2012 [25]

Region	Rice straw (kt/year)	Rice husks (kt/year)	Days available for handling rice straw/year
Northern regions (including Upper East and Upper West)	386	70	150
Volta	99	20	100
Ashanti	43	7	100

2.1.2 Rice Husk

Grate combustion is the preferred technology choice for the combustion of rice residues. Rice husks are not commonly used in combustion units as the husks will fall through the grate causing uneven air distribution, leading to uneven temperatures and combustion within the system [30]. Gasification of rice husks is an established technology that has been implemented in China, India and South East Asia successfully. They serve as decentralised units to either power a small private industry or a community and thus have been used at scales less than 1 MW [35]. Leung et al. states that though efforts of scaling up plants have been made in China, in attempts to lower electricity production costs, large size plants have not yet been widely deployed due to problems of tar treatment and secondary pollution [36]. Sudhakar et al. strongly recommend keeping the size of rice husk gasifiers small, as larger plants often face difficulty in establishing sustainable feedstock supply chains and can become dysfunctional. Furthermore they say that, at smaller sizes, these systems become ideal to serve small clusters of populations, where centralised solutions are not feasible [37]. Keeping this mind, the present study has attempted to deploy husk gasification as a decentralised electricity source for scattered populations. Thus, rather than prioritising only economies of scale, what has been considered is the size of the plant that will be required to serve population clusters of different sizes. Although larger plants might have lower costs, they might not be appropriate for the purpose of achieving Ghana's mission of universal electrification.

Previous experiences of lignocellulosic gasification plants show that a typical commercially established plant varies between 50-400 kWe however plants as small as 10 kW and as large as 2 MW have also been established [19, 20, 27, 29]. For the base case a plant of 100 kWe has been chosen for analysis. While choosing a plant location, it is vital to determine the availability of rice husk in that region. In Ghana, the Northern and Ashanti regions have clusters of mini rice mills with an average yearly turnout of 8,000 tonnes of husk and in the Volta region large-scale commercial mills produce about 5,000 tonnes husk/year. Therefore, husk residues are abundantly available to satisfy the needs of a 0.10 MWe gasifier in all regions [24]. For the base case it was assumed that the average distance between the power plant and rice mill was 5 km [24]. As rice residues are a waste product from the rice cultivation process, the economic analysis has only been considered from the collection of the waste residues once the rice has been harvested. The boundaries of the chosen technology pathways are as shown in Fig. 1.

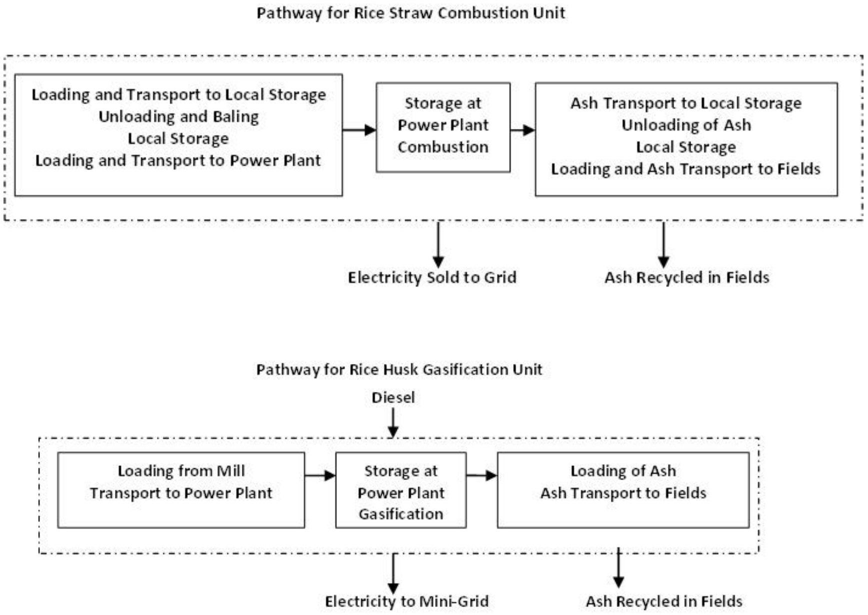

Figure 1. Pathways for power generation from rice straw and husk

2.2 Cash Flow Analysis

2.2.1 Supply of Rice Residue

The amount of residue required by the power plants was calculated as

$$Annual\ demand\ of\ residue(t) = \frac{Electrical\ output\ (MWe) * 3.6 * Operating\ hours\ \ per\ year}{Lower\ Heating\ Value\ \left(\frac{MJ}{kg}\right) * Efficiency * (1 - Moisture\ content)} \qquad (1)$$

where electrical output is the gross capacity of the power plant; operating hours indicate the time that the plant will be operating under full load; and efficiency is defined as the ratio of net electricity output to total rice residue fuel delivered to the power plant based on lower heating value (LHV) of the dry residue. The assumptions of the combustion and gasification systems are mentioned in Table 3. The specific logistics costs for rice residue supply to the power plants were adopted from Ramamurthi et al. [24], whose analysis was based on the logistics steps shown in Fig. 1 for rice straw and husk systems.

Table 3: Parameters of combustion and gasification system

	Rice straw combustion unit[a]	**Rice husk gasification unit**[b]
Plant gross power capacity (MWe)	5	0.10
Overall system efficiency	0.21	0.16
Operating hours per year	6500	5500
Lower Heating Value on a dry basis (MJ/kg)	13.5	13.5
Moisture content	0.13	0.10
Ash content in dry residue	0.18	0.20
Depreciation (years)	20	15
Maintenance costs (% of total annual capital costs)	4	12

[a] Values from [14, 30, 38] for a typical straw combustion plant

[b] Values from [14, 20, 29, 30, 39, 40] for a typical rice husk gasification plant

As seen in Tables 4 and 5, the specific cost of rice straw (39-47 USD/t) varies between different regions unlike rice husk (2.64 USD/t). This is because rice husk is available at a single location, unlike rice straw, which requires a collection area based on the straw yield of different farming land. This makes the cost of rice straw region dependent and the cost of rice husk region independent. Additionally the cost of rice straw is much higher than that of rice husk, because rice straw needs to be collected from fields, transported to storage units, baled, stored and finally transported to the power plant. This requires investment in transport, storage and baling equipment, unlike rice husk which only needs to be transported from the mill to the power plant. To increase the density of rice husks, they can be converted into pellet form. However this is not preferred as it leads to increased expenses, and most systems today use rice husk feedstock in the loose form.

The annual cost of supplying rice residue (C_{supply}) to power plants (Table 4 and 5) was calculated as

$$C_{supply}\ (USD) = Specific\ supply\ cost\ of\ residue\ \left(\frac{USD}{t}\right) * Annual\ demand\ of\ residue\ (t) \qquad (2)$$

Table 4: Levelised Electricity Cost calculations for the combustion units

	Rice straw combustion unit		
	Northern regions	**Volta**	**Ashanti**
Annual residue quantity required (kt)	47.4	47.4	47.4
Specific supply cost of rice residue (USD/t)[a]	39.0	47.5	47.9
Annual supply cost of rice residue (thousand USD)	1850.4	2254.2	2271.6
Capital costs (thousand USD)	13000	13000	13000
Annual capital costs (thousand USD)	1632.5	1632.5	1632.5
Annual maintenance costs (thousand USD)	65.3	65.3	65.3
Annual staff costs (thousand USD)	27.4	27.4	27.4
Annual quantity of ash produced (kt)	8.9	8.9	8.9
Specific cost for ash disposal (USD/t)[a]	21.1	24.9	25.3
Annual costs for disposal of ash (thousand USD)	186.7	220.5	223.8
Annual O&M costs (thousand USD)[b]	92.7	92.7	92.7
Total annual costs (thousand USD)	3789.3	4361.5	4390.4
LEC (UScents/kWh)	11.6	12.9	13.0

[a] Values from [25]
[b] Sum of staff and maintenance costs

Table 5: Levelised Electricity Cost calculations for the gasification units

	Rice husk gasification unit
Annual residue quantity required (kt)	1.0
Specific supply cost of rice residue (USD/t)[a]	2.6
Annual supply cost of rice residue (thousand USD)	2.7
Capital costs (thousand USD)	106.6
Annualised capital costs (thousand USD)	14.8
	10.9

Length of LV lines (km)	
Annualised LV transmission line costs (thousand USD)	20.5
Annual maintenance costs (thousand USD)[b]	2.6
Annual staff costs (thousand USD)	16.4
Annual O&M costs (thousand USD)[c]	19.0
Annual quantity of ash produced (kt)	0.2
Specific cost for ash disposal (USD/t)[a]	4.2
Annual costs for ash disposal (thousand USD)	0.9
Total annual costs (thousand USD)	57.9
LEC (UScents/kWh)	10.5

[a]Values from [25]
[b]Sum of maintenance costs for LV transmission lines and power plant
[c]Sum of staff and maintenance costs

2.2.2 Power Plant Capital Costs

2.2.2.1 Combustion Power Plant

Due to lack of previous experience in combustion and gasification plants in Ghana [7], investment costs for power plants have been taken from countries which have been globally most successful in establishing such types of plants at commercial scales. All costs were calculated for the date of 1st August 2013; currency conversions on this day were 1 United States Dollars (USD) = 2 Ghana Cedi (GHC); 1 USD = 60 Indian Rupee (INR).

The costs for the straw-fired grate combustion (CHP) combustion power plant were taken from a Thai study, which assesses the economic feasibility of electricity generation from rice straw combustion. In this study, the authors have obtained data of grate combustion equipment from experienced biomass combustion companies in Thailand. The capital costs as well as the raw material and labour requirements of a power plant depend on the size of the plant. Therefore a cost relationship between investment costs and plant size has been made in the study. Such correlations help to derive valid and predictable correlations between the physical and functional characteristics of a plant and subsequent costs [25]. The relationship between the two factors (size of combustion plant and investment costs) was created in the form of a general equation $Y=aX^b$; where a and b are specific coefficients, Y is the investment cost in thousand USD and X is the gross electrical output of the power plant in MW. As this will be the first straw combustion plant in Ghana, expenses such as building of the storage area, importing equipment from long-distances and the need for specially skilled workers not available in Ghana would have to be accounted for. Thus, these costs could vary depending on local site conditions. Hence an analysis has been made to see the change in electricity costs based on variation in capital costs in Section 3.1.2.

Assuming that the capital investment would partly come from local banks and partly from international loans, an interest rate of 11% was chosen for the base case. The annuity of the capital costs has been calculated using Eq. (3).

$$\alpha = \frac{i*(1+i)^n}{(1+i)^n-1} \qquad (3)$$

Where, α is the annuity factor; i is the interest rate; and n is the depreciation years as mentioned in Table 3. Fixed charges such as property insurance and property taxes were not included as they are not expected to have a strong impact on the costs [39].

The annual capital costs ($C_{Capital}$) shown in Table 4 and 5 were calculated as

$$C_{capital}(USD) = \alpha * Total\ capital\ costs\ (USD) \qquad (4)$$

2.2.2.2 Gasification Power Plant

The relationship between investment cost and plant size was taken from an Indian study [40], where the authors study the economy of scale of small to medium (10-100 kW) rice husk gasifier projects. The authors have derived this relationship based on case studies of husk gasification plants deployed in India. Studies based in India were chosen for analysis because it is the country with the most experience in small-scale gasification units, with over 15 equipment manufacturers [41] and over 1700 power plants (with sizes ranging between 2-500kW) installed [17]. Indian gasifiers are being used in SMEs as well as mini-grids to provide electricity to remote unelectrified areas [19]. Indian manufacturers such as Ankur Scientific Pvt. Limited have provided systems to a number of countries in Europe, South East Asia and South America and have installed a power plant in Uganda [20, 42].

These reports provide information about different plants that have been installed over the past ten years, which have been used for community electrification as well as for running small industries. Similar to combustion units, the capital costs of gasification plants would increase with the size of the plant due to additional resource requirement. Hence, it is reasonable to look at the investment costs for varying plant sizes in these reports, to get an understanding of what sort of relationship exists between the two factors. The relation was an equation in the form $y=cx^d$, where the coefficients c and d were 135200 and -0.1626 respectively; y is the investment costs per kW in INR and x is the gross electrical output of the power plant in kW.

As we can expect that there will be certain extra expenses for installing a system of this sort for the first time in Ghana, a sensitivity analysis of the capital costs have also been conducted in Section 3.2.1. The annuity factor and annual capital costs for the gasification power plant were calculated using Eqs. (3) and (4).

2.2.3 Transmission Line Costs

The cost for laying transmission lines for combustion plants was not taken into consideration as we assumed that it is going to be connected to the national grid using existing infrastructure. However for the gasification power plant, since it would serve as a mini-grid system, it would provide electricity through Low Voltage (LV) transmission lines. For the base case the length required for the LV lines was calculated as

$$Length\ (km) = \frac{Length\ required\ per\ household\ (km) * Population\ served}{Number\ of\ members\ per\ household} \qquad (5)$$

Where, the length of line required per household is 0.0248 km [43]; number of members per household is 5 [44] and population served is calculated using Eq.(6)

$$Population\ served = \frac{Electrical\ output\ (kWe) * Operating\ hours\ per\ year}{Per\ capita\ electricity\ consumption\ (kWh)} \qquad (6)$$

Where the annual operating hours of the plant is mentioned in Table 3; and the Ghana Energy Statistics in 2012 [45] mention that the annual per capita consumption of electricity was 357.5 kWh. However taking into consideration that the energy consumption of the rural population will be lower than the national average (but that it will increase with improved electricity provision), we assumed that the annual per capita rural electricity consumption will be 250 kWh. 2200 rural households can be served with the base case plant size of 0.10 kWe. The total cost for the transmission lines was calculated as

$$Total\ costs\ for\ LV\ lines\ (USD) = Specific\ cost\ of\ LV\ lines\ \left(\frac{USD}{km}\right) * Length\ (km) \qquad (7)$$

The specific costs of the LV lines were assumed as 13500 USD/km (as stated in personal interviews with staff at the Department of Agric. Engineering at KNUST, Ghana). The annuity factor (0.139) for the gasification plant which was earlier calculated using Eq. (3) was multiplied into the total LV line costs to get the annual LV line costs (C_{LV}).

2.2.4 Maintenance Costs

Maintenance costs were calculated as a percentage of the annualised capital cost as mentioned in Table 3; the maintenance cost for the LV transmission lines were taken as 4% of the annualised capital costs for the lines (based on interviews with the faculty at KNUST).

2.2.5 Staff Costs

Staff costs for the combustion plant included the amount required to pay 15 workers (we assumed a need of 5 workers at the plant at any given time where each worker has an 8 hour shift) a daily wage of 5 USD for 365 days a year. The staff costs of the gasification power plant included the amount required to pay 9 (we assumed a need of 3 workers at the plant at any given time where each worker has an 8 hour shift) workers a daily wage of 5 USD for 365 days.

2.2.6 Ash Disposal Costs

Ash which is produced from the combustion and gasification process of rice residues has been used as a nutrient for soil improvement in countries such as Thailand, Cambodia, China and India [15,16, 34]. Therefore, similar to the studies conducted in [30] and [46], our study assumed that ash was going to be recycled to the fields. The amount of ash produced from the systems were computed as

$$Annual\ amount\ of\ ash\ produced(t) = Annual\ amount\ of\ rice\ residue(t) * Ash\ content\ in\ rice\ residue \tag{8}$$

Where, ash content of rice straw and husk is mentioned in Table 3. The logistic steps involved in the disposal of ash are as shown in Fig.1. Relevant costs from the rice straw delivery system, mentioned in [24] can be applied for ash disposal; for example, in the Northern region, by adding up the specific costs for transport of ash from the power plant to the local storage unit (5.9 USD/t), storage (12.9USD/t) and for transport from storage units to the fields (2.2 USD/t), a specific cost of 21.0 USD/t for ash disposal was determined. The specific costs for ash disposal for the gasification system were adopted as 4.2 USD/t in all regions (Table 5), assuming that the roundtrip distance between the rice mill and fields is 20 km [24]. The annual costs for ash disposal were calculated as

$$C_{ash}(USD)=Annual\ amount\ of\ ash\ produced(t)*\ Specific\ costs\ for\ ash\ disposal(\frac{USD}{t}) \tag{9}$$

2.2.7 Levelised Electricity Cost (LEC)

LEC of the power plants were calculated using the following relationship

$$LEC\left(\frac{USCents}{kWh}\right) = \frac{C_{supply}(USD)+C_{Capital}(USD)+C_{LV}(USD)+C_{O\&M}(USD)+C_{ash}(USD)}{Operating\ hours\ per\ year*Electrical\ output(kWe)} * 100 \tag{10}$$

Where the total annual O&M costs for the power plants were calculated as

$$C_{O\&M}(USD) = Maintenance\ costs\ (USD) + Staff\ costs\ (USD) \tag{11}$$

All the required annual costs have been calculated earlier in Sections 2.2.1-2.2.6 and the results are presented in Table 4 and 5.

3 Results and Discussions

3.1 Combustion Unit

LECs of the 5 MWe base-case rice straw plant were 11.6, 12.9 and 13.0 UScents/kWh in the Northern, Volta and Ashanti regions respectively. The annual costs of supplying rice residues to the power plants contribute to about 49-54% of the total costs (Fig. 2).

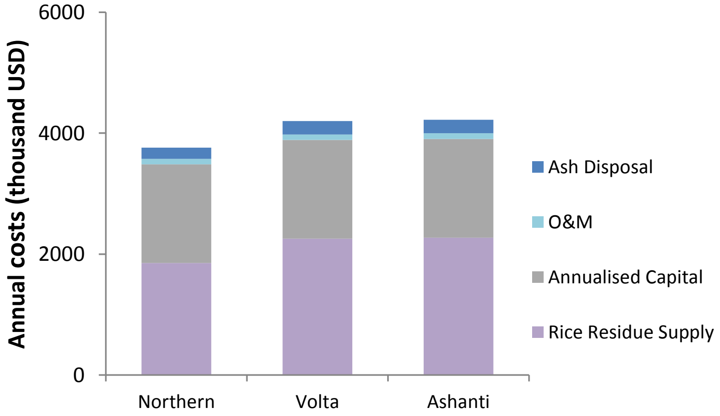

Figure 2. Break-up of annual costs for power production from rice straw combustion

LEC of the Northern region is 6% less than that of the other two regions, as annual cost of rice residue supply is 22% times less [24]. According to Ramamurthi et al. costs in rice residue supply are lower in the Northern region, due to a shorter growing season (Table 4), which makes the days available for collection of straw from fields longer [24]. Therefore the storage period and per day baling requirement are lower than the other regions. This results in lower investment requirements in the number of storage units and baling equipment, which together make up the bulk of the supply cost (79-84% of total).

Annualised capital costs contribute to 39-43% to total annual costs in all regions. Lending rates in Ghana in 2014 varied between 10.6 to 28.9% in 2014 [47]. A sensitivity analysis showed that by tripling interest rates from 9%-27%, the LEC cost increased by 55-62% in the different regions (Fig.3).

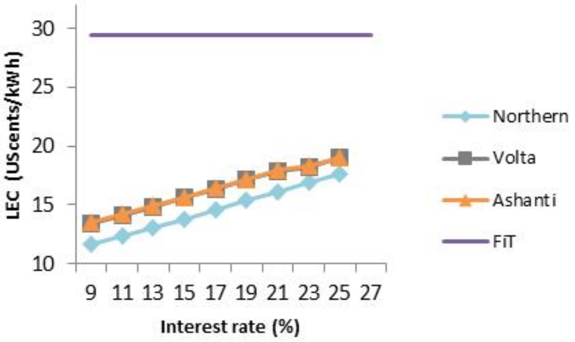

Figure 3. LEC of 5MWe straw combustion as a function of interest rate

Thus, at lending rates currently available in Ghana, the combustion plants will be viable as the Feed in Tariffs (FiT) for biomass projects in Ghana are 29.5 UScents/kWh [48].

3.1.1 Economy of Scale

The cost relationship in section 2.2.2.1 was used to evaluate the LECs of combustion plants ranging between 5-30 MW using efficiency values mentioned in [25] and specific rice supply cost values in [24] .This was only done for the Northern region (386 kt/year), as the Volta (99kt/year) and Ashanti regions (43 kt/year) do not have fuel supply to meet the demands of a plant greater than 10 MW (87 kt/year) and 5 MW (48 kt/year) respectively (Table 2). As mentioned in Section 2.1.1, since the plant becomes economically more attractive as its scale increases, we decided not to consider plants smaller than 5 MW (the largest plant size viable in all regions). Calculations showed that by increasing the plant size by six times (a six times increase in biomass requirement) there was a 40% decrease in electricity costs (Fig.4).

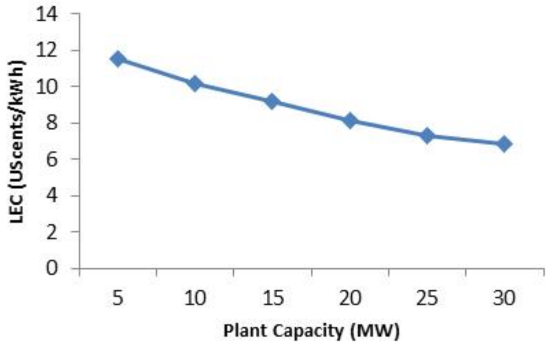

Figure 4. LEC of straw combustion as a function of power plant capacity in the Northern region

3.1.2 Sensitivity Analysis of Key Parameters

Capital and operating costs are important parameters to be estimated while evaluating the feasibility of projects. Therefore, a sensitivity analysis of certain key parameters such as capital costs, operating hours, efficiency and residue supply costs was conducted (Fig.5).

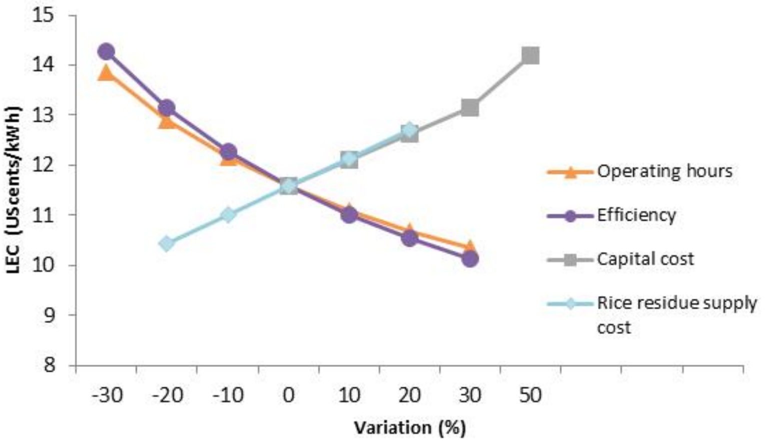

Figure 5. LEC of straw combustion as a function of key parameters

Since there can be large variations in capital costs based on local site conditions, a sensitivity analysis of capital costs (0-50%) was made on the electricity production costs. A 50% increase in capital costs, resulted in a 23% increase in LEC, therefore, it had a significant effect on the costs of the plant.

For residue supply costs, base-case assumptions state that straw is available for free and has fixed logistic parameters. However straw might have to be paid for and logistical costs could change based on varying baling, transport and storage conditions. Ramamurthi et al. states that doubling the storage and baling capacity results in a 4.9-5.4% and 13-15% reduction in costs respectively. Hence a sensitivity analysis was conducted for a ± 20% variation in straw costs, which resulted in an 11% variation in LEC. Operating parameters such as operating hours and efficiency can be affected by the level of O&M and the choice of technology. Higher operating hours and lower efficiency would require more feedstock as well as affect the amount of electricity produced. A ±30% variation in operating hours and efficiency resulted in a 25% and 29% variation in LEC respectively.

3.1.3 Applications in Ghana

In order for Ghana to meet its goal of supplying 10% of electricity from renewables by 2020, it is expected to add 500 MW of renewable capacity in the next 5 years. The total potential of biomass electricity has been estimated to range between 90-110 MW [50, 51]. Therefore, bioenergy can contribute to 20% of the total installed renewable capacity in 2020. Due to the attractive FiT offered by the Ghanaian government, rice straw combustion plants can be a viable option for the production of electricity. The suitability of straw-fired combustion units for large-scale grid-based applications doesn’t make their implementation attractive in the Northern regions. This is because the Northern regions don’t have a very extensive grid system and have many small communities which are located in remote locations, ideal for off-grid solutions. However, combustion units can be an attractive option to supplement the existing grid capacity in the rice growing regions of Volta and Ashanti, and help meet the industrial power demands in the Ashanti and Great Accra regions which accounted for over 50% of the total industrial establishments in Ghana as of 2003 [52].

3.2 Gasification Unit

LEC of the base case 0.10 MW rice husk gasification plant is 10.5 UScents/kWh. LV transmission costs (35%) and O&M (33%) contribute significantly to the annual costs as seen in Fig. 6.

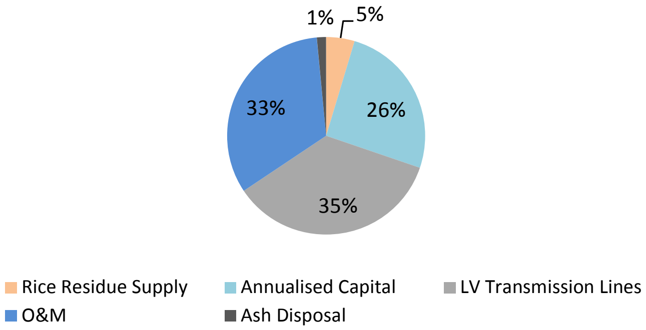

Figure 6. Break-up of annual costs for power production from rice husk gasification

As LV transmission lines significantly contribute to the overall costs of the plant (Fig. 6), a sensitivity analysis was carried out by varying the length of the LV transmission lines. This analysis was done at different roundtrip distances between the mill and power plant (10, 20 and 50 km), as a previous study [25] states that the supply price of rice husks increases significantly with an increase in transport distance. A global optimisation should be conducted to choose the appropriate distance of the power plant from the rice mills as well as consumer households.

The results showed (Fig. 7) that by increasing the length of the transmission line by 5 times from 5 to 25 km (at different round trip distances between the rice mill and power plant) the LEC of the gasification unit increased by 108-127%. However by increasing the roundtrip distance by 5 times, from 10 to 50 km between the power plant and the mill the LEC only increased by 8-18%.

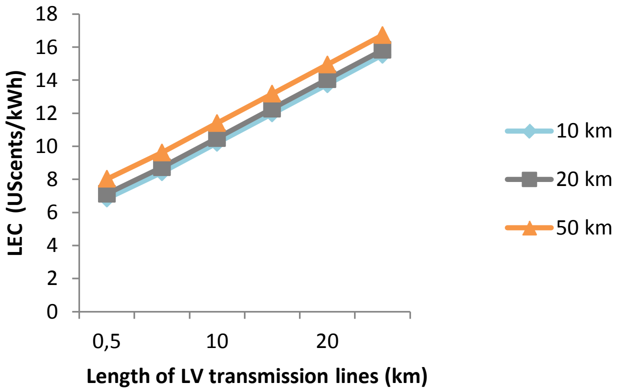

Figure 7. LEC of husk gasification as a function of length of LV transmission lines (at different roundtrip transport distances of rice husk from rice mill to power plant

Therefore, the restrictive distance is the length of the LV lines and not the distance between the rice mills and the power plant. This implies that increasing distances for husk supply will not impede the cost of the power plant very significantly.

3.2.1 Sensitivity Analysis of Key Parameters

Similar to the combustion unit (in Section 3.1.2), certain operating parameters of the gasification unit could vary due to differing site conditions. Therefore, a sensitivity analysis of key parameters was made for the gasification unit (Fig. 8).

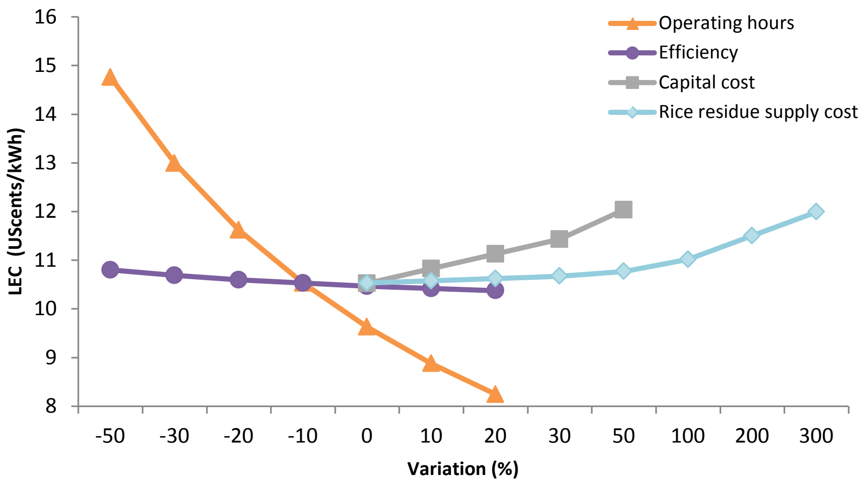

Figure 8. LEC of husk gasification as a function of key parameters

A 50% increase in capital costs resulted in a 14% increase in LEC. As 10 km is already a small round-trip distance, we only assumed an increase in the cost of rice residues in this sensitivity analysis. Ramamurthi et al. states that an increase in rice residues from 10-50 km can result in a 250% increase in rice residue prices. Therefore a sensitivity analysis was carried out for an increase of up to 300% (including costs of procuring the husk) in rice husk supply costs. A 300% increase showed a 14% variation in LEC costs. Similar to the sensitivity exercise carried out for the combustion system in Section 3.1.2, operating hours and efficiency was varied. A ±30% variation in the operating hours and efficiency resulted in a 44% and 4% variation respectively.

3.2.2 Captive Use in Small and Medium Industries

In South and South East Asia, rice husk gasifiers (100-1000 kWe) have been commercially established as a means to satisfy the electricity needs of SMEs for many decades now [14,16,27, 29, 34]. In parts of Ghana, where there is no electricity access, as well as in the regions that undergo constant power outages, rice husk gasifiers can be an economical option. Currently, diesel generators are being used as the back-up electricity production option at a cost of 17 UScents/kWh [5], which is higher than the cost of producing electricity from rice gasifiers (7 UScents/kWh, assuming SMEs will require a negligible length of LV transmission lines).

3.2.3 Rural Electrification for Remote Communities

One of Ghana's strategies to produce 10% of its electricity from renewables is to support the use of decentralised mini-grid and off-grid systems for remote communities that cannot be reached by the grid in the next 5-10 years [51]. A previous study [6] has estimated that by 2020, communities in Ghana without electricity will primarily range between 100-3000 people and that these communities will mainly be in the Northern region.

Keeping this in mind a sensitivity analysis was conducted to see how much it would cost to electrify communities of this size range with husk based mini-grids. The power plant capacity required to meet the needs of a community of a certain population was calculated using Eq. 6 and the transmission length required using Eq. 5. The cost for electrifying rural communities between sizes of 100-3000, will be 133-5 UScents/kWh (Fig. 9). For communities up to 250 people, the cost of husk gasification mini-grids is less than the average cost of grid extension (57 UScents/kWh), diesel mini-grids (102 UScents/kWh) and solar off-grid solutions (110 UScents/kWh) [43]. For communities which are smaller than 250 people, the projects may be able to take advantage of the subsidies proposed by the government as stated in the Renewable Energy Act (2011).

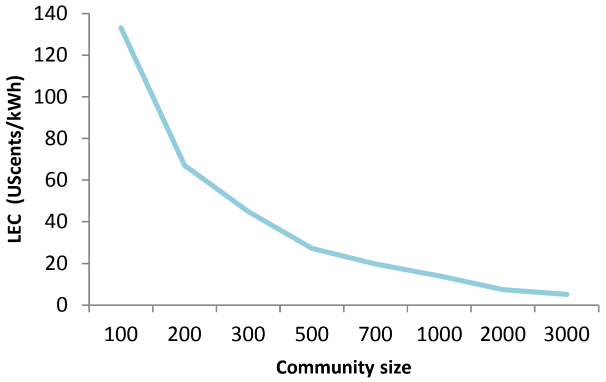

Figure 9. LEC of husk gasification as a function of population of community

Therefore, taking into consideration, the low electrifications status of the Northern regions (50%), the highest availability of rice residues and the remoteness of the village communities, this region will be the most suitable for the establishment of decentralised rice husk mini-grids. Using Eq. (1), and referring to Table 2 to get the total annual availability of rice husks in the Northern regions (70 kt), we estimate that the total annual electricity production capability from rice husks (assuming base case conditions) is about 38 GWh. Assuming that the energy need of the unelectrified population is 250 kWh per capita, (as explained in Section 2.2.3), using the total population of the Northern regions (4228116) [3] we estimate that the energy needs of unelectrified populations (50%) in these regions is annually 528 GWh. Hence, rice husk gasifiers can help by contributing to 7% of the total electricity generated for the unelectrified population of Northern Ghana.

4 Conclusions

This study assesses the feasibility of using rice residues to generate electricity in Ghana. By 2020, Ghana desires to achieve universal electrification and produce 10% of its electricity from renewable resources. This will require Ghana to think beyond conventional centralised electrification solutions. Decentralised solutions might not be a substitute for reliable grid connected electricity and some previous experiences show that communities and local utilities have preferred waiting for grid connections [3, 8, 37]. However, Alstone et al. state that decentralised solutions are still an integral option to explore, as these systems provide incremental and often substantial increases in electricity services [8]. They offer access to basic lighting and communication (phone charging facility), thereby resulting in improved health, safety (by replacing kerosene) and education, which are the first steps in climbing the ‘modern energy ladder’ [3]. Therefore, energy planners of Ghana and similar countries should consider both grid-connected and off-grid solutions while forming national electrification. While, previous studies in the SSA region have looked at the economic viability of decentralised grid-connected and off-grid solutions, there has been a focus on solar and diesel based technologies [3, 10, 11, 12], with little work on bioenergy. This study provides an insight into the way that agro- residue bioenergy solutions can contribute to electrification, with an added advantage of reducing the harmful effects of open burning of agro-residues.

As the economics of grid-supplied electricity is more attractive in densely populated areas, where there is already sufficient grid infrastructure available [3, 12], it is recommended that grid-connected rice straw combustion systems be implemented in the Ashanti and Volta regions of Ghana, which have a thriving industrial sector. These plants become economically viable at the current FiT rates offered by the Ghanaian government (29.5 UScents/kwh). Scale, efficiency and operating hour variations had the most impact on the LEC of combustion plants.

Kemausuar et al. state that 15% of the total unelectrified rural population would be well suited to be electrified with off-grid solutions in Ghana [3]. They state that these needs can be met using solar mini-grids. The LEC of husk-mini grids is 5-133 UScents/kWh for communities ranging between 3000-100 people, making them cheaper or comparable to solar mini grids whose average LEC is 110 UScents/kWh. Husk mini-grids can meet the electricity needs of up to 7% of the total unelectrified population in Northern Ghana. Hence, in addition to solar solutions, there is merit in Ghana looking at husk mini-grids projects, and there is future scope in studying the feasibility of hybrid-solar rice husk mini-grids which are being deployed in developing countries like India [53]. As most rice residue is available in the Northern regions and the rural communities which are best suited for off-grid solutions lie there, gasifier pilot projects can be initiated in that area. These projects can be given financial assistance via the schemes offered in Ghana's Renewable Energy Act (2011). This methodology of studying the cost of rice husk plants, based on the size of the population is novel and can be replicated in other rice-growing developing countries which have remote communities that are struggling to be electrified. In addition, rice gasification is a cheaper alternative (7 UScents/kWh) to satisfy the electricity needs of SMEs, which often use diesel generators as a backup (17 UScents/kWh). In conclusion, when countries are deciding the best way forward to increase their RE capacity, especially as a way to increase remote rural electrification, it is key that the economics of agro-residue based bioenergy solutions are considered, because these solutions could be the least-cost option for scattered rural populations (as in the case of Ghana).

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