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

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1. Introduction

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]. Despite this, 25% of the global population lives without electricity [2] where Sub-Saharan African (SSA) accounts for 40% of this population. In SSA, 89% of urban areas have access as opposed to 46% in rural areas [3]. International Energy Agency (IEA) predicts that even in 2030, 49% of rural SSA will still lack electricity access [2].

Ghana, a country in SSA has made relatively remarkable progress in electrification. However, even in Ghana, if electrification continues at the present rate, it will not achieve universal electrification by 2020 as planned in its National Electricity Scheme (1989) [4]. Similar to other developing countries, the major reason for slow electrification (rural electrification is at 50%) in Ghana has been an emphasis on national transmission grid expansion. This leads to ‘energy isolation’ for the rural poor with regard to grid-based electrification, where complex geography of rural areas, long transmission lines requirements, and low electricity demands of diffused rural communities makes grid extension uneconomical. There is increasing widespread agreement that energy access for the rural poor requires an integrated approach which focuses on grid-based and autonomous decentralised options [5]. Renewable Energy (RE) is modular in nature, making it ideal for decentralised technology. RE also provides independence from national-level grid-based planning, has limited capital requirements, can lower national concerns of energy security and carbon emissions and promote local employment [1]. Ghana’s Renewable Energy Act (2011), which targets supplying 10% of the country’s electricity through renewables by 2020 also actively promotes RE deployment in the country [7]. While RE options have numerous advantages, a key consideration is their economic viability. Studies show the merit in analysing costs of decentralised electrification systems in SSA, as they are often the least-cost option for scattered rural populations.
community (Table 1). It can be noticed in Table 1 that there has been a focus on solar and diesel options in SSA, and lack of information on modern bioenergy solutions.

Modern techniques of converting biomass into energy services are promising to address today’s growing energy challenges. Decentralised bioenergy has been used as a successful commercial technology for electricity generation in the developing regions of India, South-East Asia and China [10–14]. However, there has been little implementation in SSA. Mohammed et al. mention that only one biogas plant project for electricity generation has been established in Ghana [5] and Buccholz et al. studied the performance of two woody gasifier plants that were implemented for industrial purposes in Uganda [15]. Previously, modern bioenergy techniques used cereals, grains and sugar crops which could result in competition with food production, leading to rising food prices, food shortages and unsustainable changes in land use patterns [11]. Today, using lignocellulosic matter such as agricultural, forestry and municipal wastes for the generation of energy is known as Second Generation production of Bioenergy (SGB), and therefore preferred 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 ha in 2009 [16]. Agricultural rice residues (husk and straw) offer considerable potential for energy production (5.65 TJ/year) in the country [17]. In 2012, up to 70–90% of rice residues in major rice growing regions of Ghana were openly burned or dumped in landfills and water-bodies, making rice residue abundantly available for bioenergy production [18].

The availability of rice residue in Ghana and the need to prevent unsafe disposal practises, make it attractive to investigate the role of bioenergy from rice residue to meet the country’s electrification demands. As mentioned previously, economic considerations are vital to the success of a technology. This is especially true for bioenergy projects 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, therefore affecting electricity production costs [10].

Economic viability of rice straw and husk power plants have been analysed in-depth in countries such as India, China, Thailand and Vietnam which conclude that rice residue can be an economically attractive option to produce electricity [10,12,14,19]. In SSA, Fock et al. conducted a pre-feasibility analysis for setting up a 5 MW rice straw combustion plant in Mali [20]. No previous study has compared electrification costs of a decentralised grid-connected and stand-alone mini-grid bioenergy system using agricultural wastes. This is also 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.

After choosing the most suitable rice residue SGB technologies, various factors that influenced the Levelised Electricity Cost (LEC) were identified, and recommendations to minimise the LEC were made. The off-grid plant is intended to serve the specific needs of remote communities, and variation of plant scale was based on community size. LECs of chosen SGB technologies were compared with the cost of electricity production from the national grid, and other mini-grid and off-grid technologies to determine if rice residue based electricity production is cost competitive for these communities. This study is intended to assist policy-makers and other interested stakeholders understand the suitability of agro-residue based electrification options in Ghana. Based on this paper, similar analysis can be carried out in other developing countries as well.

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 determine the most suitable bioenergy conversion process for a certain region [10]. For potential implementation in Ghana, four technology pathways were initially investigated: bio-chemical processes included fermentation of rice residues for bioethanol production and Anaerobic Digestion (AD) for biogas production. These processes were found to be unsuitable for Ghana. AD is ideal for feedstock which has Moisture Content (MC) greater than 50%. However rice residues have a typical MC of only 10–30%. Additionally, AD requires water and animal dung for inoculum. Water is scarce in Northern 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 and bioethanol form rice residues in Ghana maybe an option only in the future [18]. 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

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. The feedstock used in European plants has primarily been wheat straw [20]. The amount of ash

<table>
<thead>
<tr>
<th>Authors and year</th>
<th>Research conducted</th>
<th>Technology</th>
<th>LEC (US cents/kWh)</th>
<th>Key findings</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kemausuor et al., 2014</td>
<td>A decision support tool estimated electrification costs for rural communities in Ghana over 10 years.</td>
<td>Grid extension, Diesel mini-grid, Off-grid solar PV</td>
<td>57, 102, 112</td>
<td>In addition to grid extension, an integrated energy plan using mini-grid and off-grid solutions, including RE is required to achieve electrification in Ghana</td>
<td>[2]</td>
</tr>
<tr>
<td>Adaramola et al., 2014</td>
<td>Assessed costs of electrification for rural and semi-urban areas of northern Nigeria</td>
<td>Hybrid solar PV/battery/diesel generator standalone system</td>
<td>35–38</td>
<td>Hybrid systems are the most economical stand-alone system for the region of study</td>
<td>[8]</td>
</tr>
<tr>
<td>Szabó et al., 2013</td>
<td>Applied spatial analysis for Africa to compare LECs of different electrification technologies</td>
<td>Diesel generator, Off-grid PV</td>
<td>25–55, 28–35</td>
<td>SSA can only achieve electrification through a mixture of options, including a fair share of renewables and decentralised technologies</td>
<td>[9]</td>
</tr>
</tbody>
</table>

*LEC values only taken for West African region.*
produced by a feedstock, and the content of silica and alkali in the ash mainly contributes to corrosion and fouling of a combustion system. A Danish study mentions that rice straw produces 15–20% of ash with a silica content of 75%, while wheat straw only generates 5–8% of ash with a silica content of 55% (Table 2).

However, the amount of alkali in ash from rice straw is lower (15%) than in wheat straw (25%) [20]. 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. In China, rice straw has been used as feed for combustion power plants since 2006, when the first straw-based power plant was built in the Jiangsu province. Today, rice straw is one of the primary feedstocks for straw-based combustion power projects that total 7790 MW in China [23]. As straw combustion technology has been successfully established at commercial scales, is relatively simple in construction, it looks promising for implementation in Ghana.

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 [24]. While choosing combustion power plant size, both security of biomass supply and economic considerations should be considered. Studies have shown that rice straw combustion becomes economically more favourable with increasing scales [10]. However this will be limited by the availability of rice straw in a region. An earlier study [18] estimates that each rice growing region in Ghana has approximately sufficient rice straw available to satisfy the fuel needs of a 5 MW plant (annual rice straw availability is shown in Table 3). 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 analysis. We assumed that the combustion power plant is connected to the national grid.

### 2.1.2. Rice husk

Rice husk is not commonly used in grate combustion units as husk will fall through the grate causing uneven air distribution, leading to uneven temperatures and combustion within the system [20]. Gasification of rice husk is an established technology that has been implemented in China, India and South East Asia successfully. Gasification units have not been used at scales larger than 1 MW, because they usually serve as decentralised units to power a small private industry or community [24]. Further, large sized plants face problems of tar treatment and secondary pollution [12], difficulty in establishing sustainable feedstock supply chains and can become dysfunctional. These small-scale systems hence become ideal to serve small clusters of populations, where centralised solutions are not feasible [14]. Keeping this mind, the present study has attempted to deploy husk gasification as a decentralised electricity source for scattered populations.

Previous experiences of lignocellulosic gasification plants show that a typical commercially established plant varies between 50 and 400 kW. However plants as small as 10 kW and as large as 2 MW have also been established [14,15,19]. For the base case a plant of 100 kW 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 8000 tonnes of husk and in the Volta region large-scale commercial mills produce about 5000 tonnes husk/year. Therefore, husk residues are abundantly available to satisfy the needs of a 0.10 MWe gasifier in all regions [18] (operating parameters detailed in Table 4). For the base case it was assumed that the average distance between the power plant and rice mill was 5 km [18]. As rice residues are a waste product from the rice cultivation process, economic analysis has only been considered from the collection of waste residue once rice has been harvested. Boundaries of chosen technology pathways are as shown in Fig. 1.

### 2.2. Cash flow analysis

#### 2.2.1. Supply of rice residue

The Annual Demand of Residue (ADR) required by the power plants was calculated as

$$ ADR(t) = \frac{E \times (MW)^{3.6} \times AH}{LHV \times \frac{M_{EF}}{M} \times \eta \times (1 - MC)} $$(1)

where E is gross power capacity of the power plant; AH is the annual operating hours which indicate the time that the plant will be operating under full load; $\eta$ is efficiency 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; and MC is the moisture content (weight fraction). Assumptions of combustion and gasification systems are mentioned in Table 4. Specific logistics costs for rice residue supply to the power plants were adopted from Ramamurthi et al. [18], whose analysis was based on the logistics steps shown in Fig. 1 for rice straw and husk.
Specific supply cost (SSC) of rice residue for straw includes the cost of loading and transporting loose straw to local storage units, baling, local storage of bales and transport of bales to power plant; for husk it includes cost of transport of loose husk from mills to power plant (Fig. 1).

As seen in Table 5, the SSC 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 SSC of rice straw region dependent and the cost of rice husk region independent. Additionally, 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 loose rice husk.

Annual Costs of supplying rice residue ($\text{AC}_{\text{supply}}$) to power plants (Table 5) was calculated as

$$\text{AC}_{\text{supply}} \text{ (USD)} = \frac{\text{SSC (USD/t)}}{C18} \times ADR (t)$$

**Table 4**

Parameters of combustion and gasification system.

<table>
<thead>
<tr>
<th></th>
<th>Rice straw combustion unit&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Rice husk gasification unit&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant gross power capacity (MW)</td>
<td>5</td>
<td>0.10</td>
</tr>
<tr>
<td>Overall system efficiency</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td>Annual operating hours</td>
<td>6500</td>
<td>5500</td>
</tr>
<tr>
<td>Lower Heating Value on a dry basis (MJ/kg)</td>
<td>13.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Moisture content</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Ash content in dry residue</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>Depreciation (years)</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Maintenance costs (% of total annual capital costs)</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

<sup>a</sup> Values from Refs. [11,20,25] for a typical straw combustion plant.

<sup>b</sup> Values from Refs. [11,19,20,25,26] for a typical rice husk gasification plant.

**Table 5**

Residue cost supply.

<table>
<thead>
<tr>
<th></th>
<th>Rice straw</th>
<th>Rice husk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual residue quantity required (kt)</td>
<td>47.4</td>
<td>47.4</td>
</tr>
<tr>
<td>Specific supply cost of rice residue (USD/t)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>39.0</td>
<td>47.5</td>
</tr>
<tr>
<td>Annual supply cost of rice residue (thousand USD)</td>
<td>1850.4</td>
<td>2254.2</td>
</tr>
</tbody>
</table>

<sup>a</sup> Values from Ref. [18].
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 [5], 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).

Costs for the straw-fired grate combustion power plant were taken from a Thai study, which assesses economic feasibility of electricity generation from rice straw combustion. In this study, authors have obtained data of grate combustion equipment from electricity generation from rice straw combustion. In this study, authors study small to medium (10–100 kW) rice husk gasifiers deployed in India. Studies based in India were chosen for analysis because it is the country with most experience in small-scale gasification units, with over 15 equipment manufacturers and 1700 power plants (with sizes ranging between 2 and 500 kW). Indian gasifiers are used in Small and Medium Enterprises (SME) and mini-grids in remote unelectrified areas [14]. Indian manufacturers such as M/s Ankur Scientific Pvt. Limited have provided systems to countries in Europe, South East Asia and South America and have installed a power plant in Uganda [15,27]. In this study, for our cost analysis we have assumed that the gasifiers will be similar to the GAS series by M/s Ankur Scientific Pvt. Limited, which are the most common type of plants that has been analysed in the Indian study [26]. The main parts of the gasifier are:

- Downdraft gasifier reactor with automated rice husk feeder and water-flushed ash and charcoal removal (biomass to gas conversion efficiency at 75%)
- Cyclone filter separating ash
- Producer gas water-cooling and scrubbing unit containing water
- Two parallel filter units with a coarse filter and two fine filters, each to allow constant operations during cleaning of one filter system
- One cloth bag filter
- Blower transferring producer gas to engine
- Three phase producer gas engine (producer gas to electricity conversion efficiency at 25%)

Similar to combustion units, capital costs of gasification plants would increase with plant size due to additional resource requirement. It is reasonable to look at 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 coefficients c and d were 135,200 and \(-0.1626\) respectively; \( y \) is gasifier investment costs per kW in INR and \( x \) is gross electrical output of the gasifier 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 capital costs have also been conducted in Section 3.2.1. Annuity factor and annual capital costs for the gasification power plant were calculated using Eqs. (3) and (4). The results are presented in Table 6.

2.2.2.2. Gasification power plant. The relationship between investment cost and plant size was taken from an Indian study [26], where authors study small to medium (10–100 kW) rice husk gasifiers deployed in India. Studies based in India were chosen for analysis because it is the country with most experience in small-scale gasification units, with over 15 equipment manufacturers and 1700 power plants (with sizes ranging between 2 and 500 kW). Indian gasifiers are used in Small and Medium Enterprises (SME) and mini-grids in remote unelectrified areas [14]. Indian manufacturers such as M/s Ankur Scientific Pvt. Limited have provided systems to countries in Europe, South East Asia and South America and have installed a power plant in Uganda [15,27]. In this study, for our cost analysis we have assumed that the gasifiers will be similar to the GAS series by M/s Ankur Scientific Pvt. Limited, which are the most common type of plants that has been analysed in the Indian study [26]. The main parts of the gasifier are:

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2.2.3. Transmission line costs

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. Since the gasification plant would serve as a mini-grid system, it would provide electricity through Low Voltage (LV) transmission lines. For the base case, length (L) required for LV lines was calculated as

\[
L \text{ (km)} = \frac{l_b \text{ (km)} \times P}{N_h} \tag{5}
\]

where, \( l_b \) is length of line required per household is 0.0248 km [28]; \( N_h \) is number of members per household, taken as 5 [29] and P is population served which is calculated using Eq. (6)

\[
P = \frac{E \text{ (kWe)} \times AH \text{ (h)}}{E_{\text{cap}} \text{ (kWh)}} \tag{6}
\]

where AH, annual operating hours, is mentioned in Table 4; and
Ghana Energy Statistics in 2012 [30] mention that annual per capita consumption of electricity ($E_{c_{cap}}$) was 357.5 kWh. However taking into consideration that energy consumption of rural populations will be less than the national average (but that it will increase with improved electricity provision), we assumed $E_{c_{cap}}$ to be 250 kWh. Therefore, 2200 rural households can be served with the base case plant size of 0.10 kW. Total cost for transmission lines was calculated as

$$AC_{LV} \ (USD) = SCLV \ \left(\frac{USD}{km}\right) \times L \ (km) \tag{7}$$

where, Specific Costs of LV lines ($SCLV$) were assumed as 13,500 USD/km (as stated in personal interviews with staff at the Department of Agric. Engineering at KNUST, Ghana). Annuity factor determined. Similar to the SSC of rice straw, SCA for the combustion unit depends on the region of implementation, due to differences in the growing season (explanation in Table 3). For the gasification system, SCA was adopted as 4.2 USD/t in all regions (Table 7), assuming that roundtrip distance between the rice mill and fields is 20 km [18]. Annual Costs for ash ($AC_{ash}$) disposal were calculated as

$$AC_{ash} \ (USD) = AAP(t) \times SCA \left(\frac{USD}{t}\right) \tag{9}$$

(0.139) for gasification plant calculated using Eq. (3), was multiplied into total LV line costs to get Annual Cost of LV line ($AC_{LV}$).

### 2.2.4. Maintenance costs

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

### 2.2.5. Staff costs

Staff costs for the combustion plant included the amount required to pay 15 workers a daily wage of 5 USD for 365 days a year, assuming 5 workers at the plant at any given time where each worker has an 8 h shift. Staff costs of the gasification power plant included the amount required to pay 9 workers a daily wage of 5 USD for 365 days, assuming 3 workers at the plant at any given time where each worker has an 8 h shift.

### 2.2.6. Ash disposal costs

Ash which is produced from combustion and gasification plants have been used as a nutrient for soil improvement in countries such as Thailand, Cambodia, China and India [14,15]. Our study assumed that ash was going to be recycled to fields. Annual Ash Produced ($AAP$) from the systems was computed as

$$AAP(t) = ADR(t) \times x_{ash} \tag{8}$$

where, $x_{ash}$ is ash content (weight fraction) of rice straw and husk mentioned in Table 4. Logistic steps involved in disposal of ash are shown in Fig. 1. Relevant costs from the rice straw delivery system, mentioned in Ref. [18] can be applied for ash disposal; for example, in the Northern region, by adding up specific costs for transport of ash from power plant to local storage unit (5.9 USD/t), storage (12.9 USD/t) and for transport from storage units to fields (2.2 USD/t), a Specific Cost for Ash disposal ($SC_{A}$) of 210 USD/t was included the amount required to pay 9 workers a daily wage of 5 USD for 365 days, assuming 3 workers at the plant at any given time where each worker has an 8 h shift.

### 2.2.7. Levelised Electricity Cost (LEC)

LEC of power plants were calculated using the following relationship

$$LEC \ (USCents/kWh) = \frac{AC_{supply} \ (USD) + AC_{capital} \ (USD) + AC_{LV} \ (USD) + AC_{O&M} \ (USD) + AC_{ash} \ (USD)}{AH*E(kW)} \times 100 \tag{10}$$

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

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

All required annual costs have been calculated earlier in Sections 2.2.1–2.2.6 and results presented in Tables 7 and 8.

### 3. Results and discussions

#### 3.1. Combustion unit

LEC of the 5 MW base-case rice straw plant were 11.6, 12.9 and 13.0 USCents/kWh in the Northern, Volta and Ashanti regions, respectively. $AC_{supply}$ to power plants contributes to about 49–54% of total costs (Fig. 2). LEC of the Northern region is 6% less than that of the other two regions, as $AC_{supply}$ is 22% times less [18]. Rama-murthi et al., state that SSC are lower in the Northern region, due to a shorter growing season (Table 3), which makes days available for collection of straw from fields longer (Table 3) [18]. Storage period and per day baling requirement are lower than other regions.

This results in lower investment requirements in number of storage units and baling equipment, which together make up the bulk of $AC_{supply}$ (79–84% of total).

$AC_{capital}$ contributes to 39–43% of total annual costs in all regions. Lending rates in Ghana in 2014 varied between 10.6 and 28.9% in 2014 [31]. A sensitivity analysis showed that by tripling interest rates from 9% to 27%, the LEC cost increased by 55–62% in different regions (Fig. 3). At lending rates currently available in Ghana, combustion plants will be viable as the Feed in Tariff (FIT) for biomass projects in Ghana is 29.5 USCents/kWh [32].

### Table 6

<table>
<thead>
<tr>
<th>Capital costs (thousand USD)</th>
<th>Rice straw combustion</th>
<th>Rice husk gasification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual capital costs (thousand USD)</td>
<td>13,000</td>
<td>106.6</td>
</tr>
<tr>
<td>LEC (USCents/kWh)</td>
<td>1632.5</td>
<td>14.8</td>
</tr>
</tbody>
</table>

### Table 7

<table>
<thead>
<tr>
<th>Cost for Ash disposal (SCA)</th>
<th>21.0 USD/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs (thousand USD)</td>
<td>13,500</td>
</tr>
<tr>
<td>Staff costs (thousand USD)</td>
<td>12.9 USD/km</td>
</tr>
<tr>
<td>Ash disposal costs (SCA)</td>
<td>13.0 USD/km</td>
</tr>
</tbody>
</table>

### Table 8

<table>
<thead>
<tr>
<th>Cost for transport of ash (SCT)</th>
<th>5.9 USD/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs (thousand USD)</td>
<td>13,500</td>
</tr>
<tr>
<td>Staff costs (thousand USD)</td>
<td>12.9 USD/km</td>
</tr>
<tr>
<td>Ash disposal costs (SCA)</td>
<td>13.0 USD/km</td>
</tr>
</tbody>
</table>
3.1.1. Economy of scale

The cost relationship in section 2.2.2.1 was used to evaluate LECs of combustion plants ranging between 5 and 30 MW using efficiency values mentioned in Ref. [10] and SSC values in Table 5 [18]. This was done only for the Northern region (386 kt/year), as the Volta (99 kt/year) and Ashanti regions (43 kt/year) don’t have fuel supply to meet demands of a plant greater than 10 MW (95 kt/year) and 4.5 MW (43 kt/year) respectively (Table 3). As mentioned in Section 2.1.1, since plants become economically more attractive as 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 plant size by six times (a six times increase in biomass requirement) there was a 40% decrease in LEC (Fig. 4).

3.1.2. Sensitivity analysis of key parameters

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

For SSC, base-case assumptions state that straw is available for free and has fixed logistic parameters. However, straw might have to be paid for and logistic costs could change based on varying

Table 7
Levelised Electricity Cost calculations for rice straw combustion.

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<tr>
<th></th>
<th>Rice straw combustion</th>
<th>Volta</th>
<th>Ashanti</th>
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</thead>
<tbody>
<tr>
<td>Annual supply cost of rice residue (thousand USD)</td>
<td>1850.4</td>
<td>2254.2</td>
<td>2271.8</td>
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<tr>
<td>Annual capital costs (thousand USD)</td>
<td>1632.5</td>
<td>1632.5</td>
<td>1632.5</td>
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<tr>
<td>Annual maintenance costs (thousand USD)</td>
<td>65.3</td>
<td>65.3</td>
<td>65.3</td>
</tr>
<tr>
<td>Annual staff costs (thousand USD)</td>
<td>27.4</td>
<td>27.4</td>
<td>27.4</td>
</tr>
<tr>
<td>Annual quantity of ash produced (kt)</td>
<td>8.9</td>
<td>8.9</td>
<td>8.9</td>
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<tr>
<td>Specific cost for ash disposal (USD/kt)</td>
<td>21.1</td>
<td>24.9</td>
<td>25.3</td>
</tr>
<tr>
<td>Annual costs for disposal of ash (thousand USD)</td>
<td>186.7</td>
<td>220.5</td>
<td>223.8</td>
</tr>
<tr>
<td>Annual O&amp;M costs (thousand USD)</td>
<td>92.7</td>
<td>92.7</td>
<td>92.7</td>
</tr>
<tr>
<td>Total annual costs (thousand USD)</td>
<td>3789.3</td>
<td>4361.5</td>
<td>4390.4</td>
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<tr>
<td>LEC (UScents/kWh)</td>
<td>11.6</td>
<td>12.9</td>
<td>13.0</td>
</tr>
</tbody>
</table>

*Values from Ref. [18].

Table 8
Levelised Electricity Cost calculations for rice husk gasification.

<table>
<thead>
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<th>Rice husk gasification</th>
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<tr>
<td>Annual supply cost of rice residue (thousand USD)</td>
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<td>Annualised capital costs (thousand USD)</td>
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<td>Length of LV lines (km)</td>
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<td>Annualised LV transmission line costs (thousand USD)</td>
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<td>Annual O&amp;M costs (thousand USD)</td>
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</tr>
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<td>Annual quantity of ash produced (kt)</td>
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<td>Specific cost for ash disposal (USD/kt)</td>
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<td>Annual costs for ash disposal (thousand USD)</td>
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<td>Total annual costs (thousand USD)</td>
<td>57.9</td>
</tr>
<tr>
<td>LEC (UScents/kWh)</td>
<td>10.5</td>
</tr>
</tbody>
</table>

*Values from Ref. [18].

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

Fig. 3. LEC of 5 MW straw combustion as a function of interest rate.

Fig. 4. LEC of straw combustion as a function of power plant capacity in the Northern region.
baling, transport and storage conditions. Ramamurthi et al. states that doubling storage and baling capacity results in a 4.9–5.4% and 13–15% reduction in costs respectively [18]. 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
At Ghana’s current FiT of 29.5 US cents/kWh rice straw combustion is an economically viable option. It is currently also cheaper than grid-connected solar plants, which are stated to have a tariff of 20 US cents/kWh in 2016 [33]. Straw-fired combustion units are suited for large-scale grid-based applications, and hence are not recommended for Northern regions, which don’t have a very extensive grid system and have numerous scattered rural communities. Combustion units can supplement existing grid capacity in rice growing regions of Volta and Ashanti, to help meet industrial power demands in Ashanti and Greater Accra which accounted for over 50% of the total industrial establishments in Ghana as of 2003 [34]. Rice straw combustion can hence contribute significantly to Ghana’s goal of supplying 10% of electricity from renewables by 2020.

3.2. Gasification unit
LEC of the base case 0.10 MW rice husk gasification plant is 10.5 US cents/kWh. LV transmission costs (35%) and O&M (33%) contribute significantly to annual costs (Fig. 6).

As LV transmission lines costs significantly contribute to overall costs of the plant (Fig. 6), a sensitivity analysis was carried out by varying the length of 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 [18] states that SSC of rice husk increases significantly with an increase in transport distance. Global optimisation should be conducted to choose the appropriate distance of power plants from rice mills and consumer households.

Results show (Fig. 7) that by increasing the length of transmission lines by 5 times from 5 to 25 km (at different round trip distances between the rice mill and power plant) LEC increased by 108–127%. However, by increasing the roundtrip distance by 5 times, from 10 to 50 km between power plant and mill, LEC only increased by 8–18%. Restrictive distance is length of LV lines and not distance between rice mills and power plant. Increasing distances for husk supply will not impede cost of the power plant 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. Sensitivity analysis of key parameters was made for the gasification unit (Fig. 8). 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 cost of rice residues in this sensitivity analysis. Ramamurthi et al. states that an increase in rice residues from 10 to 50 km can result in a 250% increase in rice residue prices [18]. Sensitivity analysis was carried out for an increase of up to 300% in rice husk supply costs, including costs of procuring husk. 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 operating hours and efficiency resulted in a 44% and 4% variation respectively.

3.2.2. Captive use in small and medium industries
In parts of Ghana, with poor or no electricity access, rice husk gasifiers are economical. Currently, diesel generators used for back-up electricity have an LEC of 17 US cents/kWh [4], which is higher than electricity production from rice gasifiers (7 US cents/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 for universal electrification is to support decentralised mini-grid and off-grid systems for remote communities that cannot be reached by the grid in the next 5–10 years [35]. A previous study [36] has estimated that by 2020, communities in Ghana without electricity will primarily range between 100 and 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. Power plant capacity required to meet needs of a community of a certain population was calculated using Eq. (6) and transmission length required using Eq. (5). The LEC for electrifying rural communities between 100 and 3000 people, were between 133 and 5 US cents/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, and off-grid solutions (Table 1). For communities which are smaller than 250 people, projects may be able to take advantage of government subsidies as stated in the Renewable Energy Act (2011).

Considering low electrification (50%), highest availability of rice residues and remoteness of village communities of Northern regions, this region will be most suitable for establishing decentralised rice husk mini-grids. Using Eq. (1), and referring to Table 3 to get total annual availability of rice husks in Northern regions (70 kt), total annual electricity production capability from rice husks (assuming base case conditions) is 38 GWh. Assuming, the energy requirements as 250 kWh per capita (as explained in Section 2.2.3), and using the total population of the Northern regions (4,228,116) [2] we estimate that the energy needs of unelectrified populations (50%) in these regions is annually 528 GWh. Hence, rice husk gasifiers can help contribute to 7% of total electricity generated for unelectrified population of Northern Ghana.

4. Conclusions

For Ghana to achieve universal electrification and produce 10% of its electricity from renewables, it will need to think beyond conventional centralised electrification. Decentralised solutions might not substitute grid connected electricity, but are integral in offering access to basic electricity services, which is the first step in climbing the ‘modern energy ladder’ [6]. This study analyses how decentralised agro-residue bioenergy solutions can contribute to Ghana’s electrification aspirations.

LEC of grid-connected rice straw combustion plants are economically viable at current FiT rates (29.5 US cents/kWh) and are most suited for Ashanti and Volta regions which have advanced grid infrastructure and a thriving industrial sector. Scale, efficiency and operating hour variations had the most impact on the LEC of combustion plants.

Husk plants can meet the electricity needs of up to 7% of the total unelectrified population in Northern Ghana. LEC of husk-mini grids is 5–133 US cents/kWh for communities ranging between 3000 and 100 people, making them cheaper or comparable to solar mini grids whose average LEC is 130 US cents/kWh. There is merit in looking at husk mini-grids projects and also the feasibility of hybrid-solar rice husk mini-grids which are deployed in developing countries like India. Rice gasification is a cheaper alternative (7 US cents/kWh) to satisfy the electricity needs of SMEs, which often use diesel generators as a backup (17 US cents/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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