ELECTRICITY PRODUCTION FROM RICE HUSK GASIFICATION FOR RURAL ELECTRIFICATION IN GHANA: AN ECONOMIC AND ENERGETIC PERSPECTIVE

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ABSTRACT: Decentralised systems can help accelerate electrification in countries struggling to achieve universal electricity access through centralised grids. Using the case of Ghana, a country where 50% of the rural population is unelectrified, this paper examines the potential of using rice husk gasification mini-grids to electrify the country's unelectrified rural communities. Economic studies and energy balances of the gasification system were conducted. In major rice growing regions of Ghana, rice husk gasifiers have the potential to electrify 8% of the currently unelectrified communities. Levelised Electricity Costs (LEC) of the gasification units ranged between 20-84UScents/kWh, when used for communities ranging between 5000-100 people. Energy balance assessments showed that the total input of fossil fuels required for production of electricity is higher than the output. Hence, it is not energetically attractive to use a dual-fuel gasifier.Single-fuel producer gas systems are recommended from an energetic perspective, as there is a 99% renewable energy input.
Keywords: decentralised; rural development; rice husks; gasification; economical aspects; energy balance

1 INTRODUCTION

Access to modern energy services is fundamental to improving quality of life, deployment of health and educational infrastructure and socio-economicdevelopment. However, today 25% of the world's population lives without electricity[1]. There is an urban-rural divide in the electricity access challenge, with the International Energy Agency (IEA) stating that in 2012, the global urban electrification rate was 94%, as compared to 68% in rural areas [2].The worst electrification rates are in Sub-Saharan Africa (SSA), which had an electrification rate of 32% in 2012 (urban – 59% and rural -16%). Ghana, an SSA country, has made remarkable progress in electrification in the region (72% electrified). However, it also faces the challenge of electrifying its rural population. This has resulted in a 100% urban and 50% rural electrification rate [2].

Despite successive governments implementing various policy mechanisms to increase access to electricity services [3], according to a United Nations Energy Programme study in 2012 [4], if electrification continues at the present rate, Ghana will not be able to achieve universal electrification by 2020 as planned in their National Electrification Scheme. Similar to a number of developing countries, the major reason for the slow growth of electrification in Ghana has been an emphasis on extension of the national transmission grid[5].

The remote and scattered locations and low consumption patterns of rural populations (as in the case of Ghana), makes grid extension uneconomical. Therefore, there is increasing acceptance that in order to achieve universal electrification, an integrated approach which promotes autonomous decentralised systems in addition to the extension of the central grid is required.

Due their modular nature Renewable Energy (RE) solutions are well-suited for decentralised applications, and solar, small-hydro and biomass solutions are increasingly being deployed in rural areas in developing countries [6].A key driver to promote RE in Ghana is the Renewable Energy Act (2011), which seeks to supply 10% of the country's electricity through renewables by 2020[7].

Before implementing RE solutions, it is important to study the feasibility and benefits of implementing these projects. This information allows policymakers to undertake informed decisions on establishing national schemes for these technologies. Recently, a few studies have attempted to study the feasibility of establishing decentralised technologies in SSA[8, 9, 10].These studies show that there are regions in the SSA which have a high potential to implement decentralised electrification systems. Further, these decentralised systems can be the least cost option for certain sections of rural communities..

Modern bioenergy solutions can play an important part in increasing the electrification ratesof developing countries like Ghana. These solutions not only provide sustainable energy services, but can also promote social, agricultural and economic growth as well as employment opportunities [11, 12].

The 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 crops to the national food basket and land use in Ghana, 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 [13]. Hence, agricultural wastes from rice production in the form of husk and straw, offer considerable potential for energy production (5.65 TJ/year) [14]. According to Ramamurthi et al., 70-90% of rice residues in major rice growing regions of Ghana are openly burned or dumped in landfills and are hence abundantly available for bioenergy production[15]. It is thus worth investigating the role of rice residues as a cheaply available resource that can be exploited for the production of bioenergy to meet the country's electrification demands.

This study attempts to analyse the feasibility of implementing rice residue based SGB conversion technologies to help meet Ghana's rural electrification challenge. After choosing the most appropriate technology for implementation, this paper analyses the economics (LEC) and net energy input/output of the system. This was done through a life-cycle analysis based method.

LEC is an important aspect of any technology, as it indicates the economic feasibility of implementing a project.

Energy analyses for bioenergy systems such as ethanol and methanol production, micro-algae conversion, direct-fired power generation and rice straw gasification [16, 17, 18, 19]have been conducted in the past. This is the first time that an attempt has been made to analyse the energetic aspects of a rice husk gasification system.

The analysis and information presented in this study is relevant for many developing countries to estimate the economic and energetic viability of off-grid electrification through the use of agro-residues.

2 METHODS

2.1 Husk Gasification Technology

The choice of a suitable bioenergy conversion process depends on many factors such as type and availability of biomass, socio-economic conditions and end-user applications[20].

Husk gasification systems have been commercially establishedin 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 a size less than 1 MW[21]. The present study has attempted to deploy husk gasification as a decentralised electricity source for scattered populations.

Previous experiences of lignocellulosic gasification plants in India, China and South East Asian countries, show that a typical commercially established plant varies between 100-400 kWe. However, plants as small as 10 kW and as large as 2 MW have been established as well[22, 23, 24]. For the base case a plant of 250kWe has been chosen for analysis. The Northern and Ashanti regions of Ghana 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 0.25 MWegasifier[15]. Most commercially established gasification systems are dual-fuel systems, as they are cheaper and in case there is a lack of feedstock, the system can still run on diesel[22, 25]. Therefore, for the base case, it was assumed that the gasification unit is a dual-fuel system with diesel being the pilot fuel. The roundtrip distance between the power plant and rice mill was taken as 10 km in the base case [15]. Since huskis a waste product from the rice cultivation process, the economic analysis has only been considered from the collection of husk at mills. The boundary of the chosen technology pathway is shown in Fig. 1.

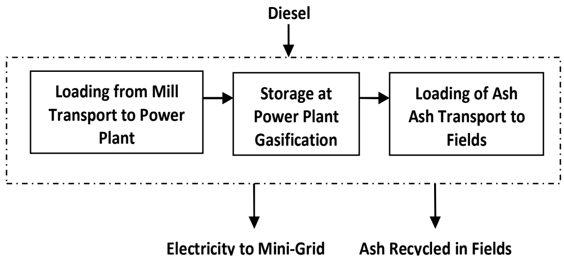

Figure 1: Pathway for Rice Husk Gasification

2.2 Cash Flow Analysis

Rice husk supply costs were calculated based on the specific supply costs mentioned by Ramamurthi et al. who followed the logistical steps mentioned in Fig.1[15] and the amount of the amount of rice husk required by the power plants was calculated as

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

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; 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 gasification system are mentioned in Table I.

Table I: Parameters for base case gasification unit

Parameter	Value
Plant gross power capacity (MWe)	0.25
Overall system efficiency	0.17
Operating hours per year	5500
LHV on dry basis (MJ/kg)	13.5
Moisture content	0.10
Ash content in dry husk	0.20
Depreciation (years)	15
Maintenance costs (% of total annual costs)	12

Most dual-fuel gasification systems have between 20-30% of replacement from diesel [26, 27]. Therefore, weassumed that there will be 25% of diesel replacement in the system and the fraction of electricity output by husk gasification would be 0.75.

Due to a lack of experience in gasification plants in Ghana [5], investment costs have been taken from countries which have been globally most successful in establishing such types of plants at commercial scales. The investment costs for dual-fuel gasification power plants of different capacities were taken from two reports that analysed the techno-economic parameters of successful gasifiers in India which use lignocellulosic feedstock including rice husk[22, 28].These reports contain information about plants that have been installed over the past ten years, and have been used for community electrification as well as for running small industries. 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.This shows us that the capital costs of power plants are primarily driven by the capacity.

This correlation has been used while analysing cost variations due to different plant sizes. Using an equation in the form $y=cx^d$, the coefficients c and d were found to be 677.1 and 1.00 respectively; y is the investment cost in thousand USD and x is the gross electrical output of the power plant in MW. This correlation falls in line with other studies which have used similar correlations for studying thermo-chemical power plants in the European and Asian context [29].

The investment costs only take into consideration costs of the power plant. However, as this will be the first husk gasification plant in Ghana, additional 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. Hence, a 30% increase in capital costs has been considered in our study.

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 was calculated using Eq. (2).

$$\alpha = \frac{i*(i+1)^n}{(i+1)^n-1} \quad (2)$$

Where, α is the annuity factor; i is the interest rate; and n is the depreciation years as mentioned in Table I. 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 [28]. The annual capital costs were calculated using the above annuity factor.

The gasification power plant, would serve as a mini-grid system, providing electricity through Low Voltage (LV) transmission lines. Hence, costs of the LV transmission lines were estimated. Thelength of the transmission line would vary based on the size of the population that the system served.

Operation and Maintenance (O&M) costs included the maintenance costs of the plant, staff required to operate the plant and the diesel used in the power plant. Maintenance costs were calculated as a percentage of the annualised capital as mentioned in Table I; and the maintenance cost for the LV transmission lines were taken as 4% of the annualised capital costs for the transmission lines.

The staff costs were estimated for the workers in the gasification plant.

The annual amount of diesel required for the gasification power plant was calculated and the cost of diesel in Ghana was multiplied into this value.

Ash, which is produced from the gasification process of rice residues has been used as a nutrient for soil improvement in countries such as Thailand, Cambodia, China and India [30, 31, 32]. Similarly, our study assumed that the ash producedwould be recycled in the fields. The amount of ash produced from the systems was computed and the cost of disposal of ash was taken from Ramamurthi et al.

LEC for the power plant was calculated using the following relationship

$$LEC\left(\frac{USCents}{kWh}\right) = \frac{C_{supply}(USD) + C_{Capital}(USD) + C_{LV}(USD) + C_{O\&M}(USD) + C_{ash}(USD)}{Operating\ hours\ per\ year * Electrical\ output\ (kWe)} * 100 \quad (3)$$

2.3 Energy Balance

This study considers that rice husk is a waste product of rice processing, therefore for the energy balances, rice cultivation, fertilizer input and agricultural land usage has not been taken into consideration. As the manufacture of transport vehicles, materials and building construction are typically less than 3% of the total energy consumptions in the system, they were not included in the energy balance calculations[17].

2.3.1 Energy Indicators

In order to assess the energetic sustainability of the husk gasification process, different energy indicators were used.

Net Energy Value (NEV) which evaluates the total amount of primary inputs required to produce a unit of energy. It determines the energetic attractiveness of an energy conversion option. A positive value generally estimates the extent of feasibility of the process[17].

$$NEV = \frac{Energy\ produced - Energy\ required\ for\ production}{Energy\ produced} \quad (4)$$

While evaluating renewable conversion processes, like bioenergy it might be more useful to look at the Net Renewable Energy Value (NREV). This gives us an idea of how energetically attractive the option is with respect to fossil fuel inputs in the system.

$$NREV = \frac{Energy\ produced - Non - RE\ required\ for\ production}{Energy\ produced} \quad (5)$$

Another valuable indicator that can help assess a renewable source's contribution to energy security [17] is the energy yield. This also, only considers the fossil fuel input of the system.

$$Energy\ yield = \frac{Energy\ produced}{Fossil\ fuel\ energy\ input} \quad (6)$$

2.3.2 Material Inputs

An earlier field study by Ramamurthi et al. felt that Motorking tricycles, which are locally used widely in Ghana were best suited to transport the rice husk and ash to/from the power plant[15].

Using the husk requirement, which was calculated from Eq. (1), we can calculate the number of Motorkings required for the transport of husk from the mill to the power plant as

$$Number\ of\ vehicles = \frac{Annual\ demand\ of husk\ (t) * Time\ for\ one\ roundtrip\ (h)}{Working\ hours\ per\ day * \ Days\ of\ usage * Weight\ capacity\ per\ vehicle\ (t)} \quad (7)$$

Where the working hours per day pertain to the working staff; days of usage is considered annually; and weight capacity per vehicle is the amount of husk carried by each vehicle during one trip.The time for one roundtrip is calculated as

$$Time\ for\ one\ roundtrip\ (h) = Loading\ and\ unloading\ time\ per\ roundtrip(h) + \frac{Roundtrip\ distance(km)}{Speed\left(\frac{km}{hr}\right)} \quad (8)$$

Where roundtrip distance is between the rice mills and power plants (Table II); and loading and unloading distance per roundtrip and speed of Motorkingsare also mentioned Table II.

In order to model the per unit delivery cost of rice residues and produce scalable results, the equipment and staff requirements havebeen considered in fractions. However in a feasibility study where actual investmentsare being considered, equipment and staff requirements would need to be included in whole numbers [15].

Table II: Parameters of the Motorking

	Value[a]
Working hours per day	8
Days of usage in a year	300
Weight capacity per vehicle (t)	0.5
Loading and unloading time per roundtrip (h)	1
Roundtrip distance (km):	
Mill and power plant	10
Power plant and ash disposal fields	20
Speed (km/h)	25
Fuel consumption (l/h)	1.47

[a]Motorking values from [15]

The annual fuel requirement for the Motorkings to transport the husk from mills to power plantwas calculated as

$$Annual\ \ fuel\ requirements\ (l) = Usage\ hours\ per\ day * Days\ of\ usage * Number\ of\ vehicles * Fuel\ consumption\ (\tfrac{l}{h}) \quad (9)$$

Where fuel consumption and days of usage are given in Table II;number of vehicles was calculated using Eq. (10) and usage hours per day was calculated as

$$Usage\ hours\ per\ day = Working\ hours\ per\ day * (1 - \frac{Loading\ and\ unloading\ time\ per\ roundtrip\ (h)}{Time\ for\ \ one\ roundtrip\ (h)}) \quad (10)$$

The fuel assumed to be used by Motorkings is petroleum. Two inputs were used at the power plant,rice husk (calculated from Eq. (1)) and diesel (as it is a dual-fuel system), which was calculated.

The amount of ash produced was calculated. This value was used (instead of annual demand of husk) in Eq. () to calculate the number of Motorkings required for ash disposal. The roundtrip distance between the fields and power plant is given in Table III. The fuel requirement for these vehicles wascalculated usingEqs. (9) –(10).

It was assumed that each Motorking has one staff member, who will load and unload the husk/ash as well as drive the vehicle. The number of staff required at the power plant has been mentioned in Section 2.3.

2.3.3 Energy Input and Output

The fuel inputs (petrol, diesel and husk), were converted to energy inputs by multiplying the required fuel amounts into their LHVs. The energy inputs for staff was calculated using Eq. (11) from [17]

$$Energy\ value\ of\ labour\left(\frac{MJ}{day}\right) = \frac{Daily\ wage(USD) * Per\ capita\ energy\ consumption(MJ)}{Per\ capita\ GNI\ (USD)} \quad (11)$$

The energyvalues of labour was 15 MJ/day.This was further split into renewable and non-renewable content. The energy indicators mentioned in Section 2.4.1, were computed using Eq. (4)-(6) and the results are shown in Table III.

Table III: Energy Indicators

Indicator	
Net Energy Value	-5.0
Net Renewable Energy Value	-0.1
Energy Yield	0.9

3 RESULTS AND DISCUSSIONS

3.1 Economic Analysis

LEC of the base case 0.25 MW rice husk gasification plant is 19.3UScents/kWh. O&M constitutes the major part of the total annual costs. Hence the O&M costs were further broken up and it was observed that the cost of diesel at the power plant accounted for 86% of the total the O&M costs.

Today, there are systems which utilise lower amounts of diesel, or run solely on producer gas. Therefore as diesel input in the power plant contributes heavily to the LEC, it might be advantageous to get a gasification system which uses lesser amounts of diesel. However, suppliers state that these systems have higher capital costs. Unfortunately, due to a lack of literature on the costs of these systems, we could not include the exact costs of decreasing the amount of diesel input. To get an idea of the trade-off between using a single-fuel system and the increased capital costs, a sensitivity analysis was carried out as shown. Unless the cost of the single-fuelsystem is 7 times the cost of the dual-fuel system, it is economically favourable to use the former.

A global optimisation wascarried out in order to choose the appropriate distance between the power plant and rice mills and consumer households. The length of the

transmission lines (at different round trip distances between the rice mill and power plant) and the roundtrip distance were increased by 5 times. It showed that the restrictive distance is the length of the LV lines and not the distance between the rice mills and power plant. This implies that increasing distances for husk supply will not impact the cost of the power plant very significantly.
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 in remote communities that cannot be reached by the grid in the next 5-10 years [33]. A previous study [4] has estimated that by 2020, communities in Ghana without electricity will range between 100-5000 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. The cost of husk gasification mini-grids is less than the average cost of grid extension estimated by [34], diesel mini-grids and solar off-grid solutions for communities ranging between 200-5000 people.

Using Eq. (1), and referring to Ramamurthi et al. to get the total annual availability of rice husks in the Northern regions (70 kt)[15] we estimate that the total annual electricity production capability from rice husk was calculated (assuming base case conditions). Assuming that the energy need of the unelectrified population is 250 kWh per capita, using the total population of the Northern regions we estimate that the energy needs of the unelectrified populations.Rice husk gasifiers can help contributeto 8% of the total electricity generated for the unelectrified population of Northern Ghana.

3.2 Life-cycle Energy Analyses

89% of energy requirement for the gasification system comes from renewable sources, with only 18% from fossil fuel input. Among the fossil fuel input, diesel going into the power plant accounts for 98% of the total input.

The NEV of this system is negative, and this typically indicates that the system is unattractive for adoption from an energetic point of view. However, in the case of renewables, the NREV is a more suitable indicator to study a fuel's attractiveness. This is because it gives us an idea of how much fossil fuel goes into the system. However, the NREV is also negative. This implies that there is more fossil fuel input going into the system that output.The ratio of energy output to fossil fuel input is 0.9. An increase of 5% in the biomass fraction (80%) and (20%) diesel, will be sufficient to turn theNREV to 0.

If we use a single-fuel producer gas system, we see that although the NEV is still negative (-5.6), the NREV is positive (0.9), and the energy yield is higher 30.8. Therefore, a single-fuel producer gas system is the preferred option for implementation.

4 CONCLUSIONS

By 2020, Ghana aims to achieve universal electrification and produce 10% of its electricity from renewable sources. Today, 100% of its urban population has access to electricity, but only 50% of its rural population is electrified. This is primarily due to a focus on grid extension solutions, which becomes unfeasible for Ghana's diffused rural communities which have small populations.

Thus, for Ghana to achieve its aforementioned goals, it should look beyond conventional electrification solutions. Stand-alone husk gasification systems are an attractive solution for these diffused communities. They have been successfully employed in other developing countries as a rural electrification solution [27, 30, 35]. An economic analysis of rice husk gasifiers showed that the LEC ranged between 19-84UScents/kWh to electrify communities between 5000-100 people. A single-fuel gasification system only becomes economically unattractive if it costs more than 7 times the dual-fuel system.

Our energetic analysis shows that a dual-fuel system has a negative NREV. This indicates that there is more input fossil going into the system than output. This is due to the large amount of diesel used at the power plant. Thus, it is recommended that a single-fuel system which gives a positive NREV be used. 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 very important to consider the economics of agro-residue based bioenergy solutions because these solutions could be the least-cost option (as in the case of Ghana).

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7 LOGOS

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