Technical and sustainability assessment of power production system based on cotton stalk and rice husk gasification in an isolated area in Burkina

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***Abstract*—Biomass gasification systems may be relevant for decentralized power generation from these residues in the isolated areas. This work deals with the analysis of both the technical and economic feasibility, and then the environmental and social impacts of a 95 kWe gasification plant project in order to generate electricity for Badara village in Burkina. Two biomasses feedstock: cotton stalk and rice husk are used. Mass and energy balances of the processes were performed to assess technical performance. Levelized cost of electricity (LCOE) analysis is used to estimate the production cost of the two biomasses options. The environmental impacts were assessed by using a Life Cycle Assessment (LCA) approach. The results show that the valorisation of the rice husk is the solution that offers the low production cost (0.34 €/kWh) compared to cotton stalk (0.38 €/kWh) despite its low electricity efficiency (11.9% against 12.6%). Nevertheless, the use of the cotton stalks is most interesting in terms of direct job creation (9.58 full-time equivalent jobs /year against 8 full-time equivalent jobs /year). Concerning the environmental issue, the two biomasses present the similar impact levels. This assessment represents an important step that could assist the policy maker to make a relevant decision for this local conditions and available resources.**

Keywords— *electricity; biomass; gasification; sustainability; simulation models, Burkina Faso.*

I. INTRODUCTION

Burkina is a West African landlocked Sahelian country characterized by low electrification rates; about 1% in rural areas [1]. Indeed, electricity is currently, produced through fossil fuel power and hydro power stations and 95% of electricity are consumed in urban areas. Thus, electricity needs in peri-urban and rural areas remain uncovered [2]. However, the country has significant recoverable energy resources including biomass (rice husk, corn cob, cotton stalks, etc.) which could play a major role in meeting the steady growing energy needs. Nearly 97,000 tons/year of potential of the rice husks can be locally recoverable in rural areas [3]. Since its creation in 2007 according to the law N° 027-2007 / AN /2007, the Rural Electrification Fund (REF), in charge of the "Rural Electrification" sector, works for the promotion of renewable energies with the support of the international development organisations. To this end, a total power capacity about 86 kWe of small-scale biomass gasification system has so far been installed since 2009, mainly for stand-alone applications. Other rural village's electrification projects from isolated mini-grids are also under study. The first feedbacks have confirmed the relevance of this system. But, they also have shown that there are real constraints related to the regularity of biomass quality (moisture content, size) and to local conditions (input cost, availability of local skilled worker, management of wastewater etc.), that threaten the sustainability of these systems. Therefore, it is important to assess the feasibility and durability of these power production system based on biomass gasification.

Thus, the main goal of this study is to assess both the technical performance and sustainability of biomass gasification system for generation of electricity in an isolated area under the Burkina local conditions. To achieve this objective, a simple simulation models was established under MATLAB programming tool.

II. METHODOLOGY

A. *Assessment criteria*

Performing the assessment of biomass gasification system in local conditions and biomass resources available is focused on several criteria: These criteria were set out by using external functional analysis approach.

- Technical: overall electricity efficiency, system availability;
- Economic: investment cost, operating cost, electricity production cost;
- Environment: human toxicity carcinogenic effects, human toxicity non-carcinogenic effects, freshwater ecotoxicity, respiratory effects;
- Social: direct jobs generated.

B. *Study area : Badara village*

The locality of Badara is located in Province of Kénédougou,in Burkina Faso. Its population is estimated at about 2000 people in 350 households with 6 people/ household on average. Hourly electrical load profile estimated is illustrated in figure 1, including 10% online loss of distribution network [3].

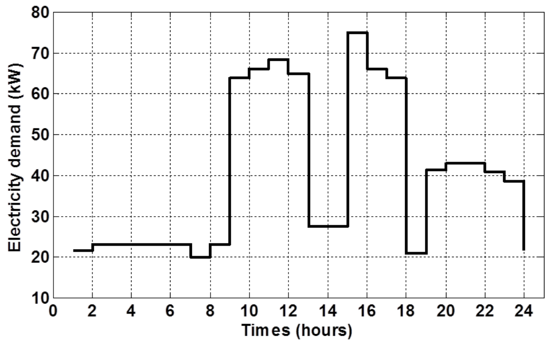


Figure 1: Electrical load profile estimated of Badara village (adapted from [3])

The biomasses available in the study area are cotton stalk and rice husk as shown in figure 2. According to expertise data of 2014 [3], the potential of cotton stalk that can be collected in the Badara village and neighboring localities within a 10-km radius is estimated at 1070 tons/year. The rice husk can only be collected in neighboring localities. Based on the production capacities of the husking plants [3], about 1300 tons/year can be available.

Figure 2: Biomass resources: cotton stalk (left) and rice husk (right)

C. *Proposed electricity generation system configuration*

1) *Biomass conversion technology*

The proposed biomass conversion technology is based on an existing commercial FBG 60 ‘’Ankur Scientific Energy Ltd.’’ in Burkina. The main components are shown in figure 3. Biomass is converted into the combustible gas in a fixed bed reactor (1) using atmospheric air as gasifying agent. The produced gas commonly called syngas leaves the gasifier through the bottom outlet. It is then cleaned and coaled in the series of equipment including high temperature filter (2), two water heat exchangers (3), mist eliminator (4), dry saw dust filters and security bag filter (5); before being combusted in the spark-ignition engine-generator (6). In the lower part of the gasifier, a screw conveyer removes ashes from the gasifier. Likewise, in the lower part of the heat exchangers, the tar condensates are collected. A diesel generator is provided for the start-up phases.

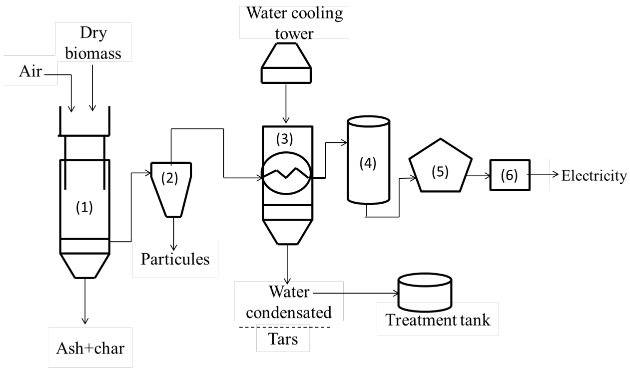


Figure 3: Simple diagram of biomass technology conversion

2) *System production capacity and operation*

To satisfy the above demand profile at its peak load, the system production capacity to be installed is set at 95 kWe, assuming an average power of 10 kWe of the auxiliaries and 90% maximum operating load. The system is assumed to running for 24 h and 335 days per year either 8040 h/year. We consider 720 h (30 days/year) for maintenance and unforeseen interruptions.

3) *Labor needs and management of ash residues and tars*

According to the main operating tasks such as the preparation of the biomass and the follow-up of the conversion process, the workforce required for the cotton stalks was estimed to 17 persons and 9 persons for rice husk. At total, of three skill technicians and an engineer are included on each workers team.

The ashes from gasification process can use as fertilizer. However, due to the lack of a local market that regulates its sale, the incomes from the commercialization of ash residues are not considered in our basic hypothesis. The tars produced are collected and release in local environment.

D. Technical assessment models

The overall system efficiency is defined as the product of gasifier efficiency and the performance of gas engine (equation 1).

$$\eta_{global} = \eta_{gas} . \eta_{engine} \tag{1}$$

η_{global} – Overall efficiency (%); η_{gas} – gasification efficiency; η_{gas} – electrical efficiency of gas engine-generator (%). The gasification efficiency expressed as the cold gas efficiency [4] was computed as the ratio of the energy content of the syngas to the energy content of the biomass feedstock on a lower heating value basis (equation 2).

$$\eta_{gas} = \frac{m_{gas}.LHV_{gas}}{m_{bio}.LHV_{bio}} \tag{2}$$

η_{gas} – gasification efficiency (%) ; m_{gas} – mass of syngas (kg); m_{bio} – mass of biomass (kg); LHV_{gas} – low heating value of syngas (kJ/kg); LHV_{bio} – low heating value of biomass (kJ/kg).

To obtain this value, thermodynamic equilibrium model widely adopted in the literature [5]–[7] is used in this analysis in order to take into account the characteristics of biomasses available in assessing the sustainability of production system. The main fuel properties of biomasses used in this analysis such as proximate analysis, ultimate analysis was reported by [8], [9]. However in our context, the drying of biomass is done by natural route with difficult control. Hence, the moisture content of cotton stalk in our basic hypothesis is assumed to be 15 % and 12 % for rice husk. The gasification temperature is set at 800°C.

The efficiency of gas engine is defined in equation 3 as the ratio of the energy output to the energy contained in producer gas. However, it is noted that it is highly dependent on its operating conditions. Hence, we use the experimental data from [10] for modeling the efficiency of gas engine according to the load factor. This has allowed to estimating the electrical efficiency over each hour (t).

$$\eta_{engine} = \frac{E_P}{E_{gas}} \tag{3}$$

η_{engine} – Electrical efficiency of gas engine-generator (%); E_P – energy output (kWh); E_{gaz} – energy content of syngas (kWh).

Concerning the system availability it is expressed in accordance with dependability concept as:

$$SA = \frac{MTBF}{MTBF + MTTR} \tag{4}$$

SA – System availability (%); $MTBF$ – mean time between failures (h); $MTTR$ – mean time to repair (h). Because of the lack of data, these parameters are estimated on expert opinion.

E. Economic assessment models

Capital cost is calculated as the sum of equipment costs (gasifier with ancillaries and gas engine) plus, transport and insurance, installation and civil works, stock of spare parts, engineering, commissioning and training and contingency costs. Land cost is also included. The costs of the equipment for the size of proposed system were estimated according to the capacity factor method [4]. With this method the cost is estimated considering the reference cost and size of a system existing at Burkina as described in equation 5.

$$C_{Eq} = C_{ref} . \left(\frac{S}{S_{ref}} \right)^m \tag{5}$$

C_{Eq} – Costs of the equipment of proposed system (€); S – production capacity of proposed system (kWe); C_{ref} – reference cost of equipment of existing similar production system (€); S_{ref} – production capacity of existing similar production system (kWe); m – extrapolation factor.

The parameter m is set in our study at 0.65 based on experience feedback [11]. The costs of others capital sub-components are estimated by using factor method. The principle is to assume that these costs are proportional to the capacity of the installed equipment. These factors are reported in table 1. The hypotheses are based on data of a biomass gasification project (confidential report).

Table 1: Cost factors for capital cost calculation

Capital sub-components	Cost factor
Installation and civil work	27 %
Transport and insurance	20 %
Stock of spare parts	16 %
Engineering,	15 %
Commissioning and training	22 %
Contingency	5%

The operating costs are the sum of the following items: maintenance, consumables and utility such as water, biomass, diesel, and dolomite, labor cost. Maintenance costs have been calculated as a percentage of capital cost. Based on literature, we assume it at 4 % for cotton stalks and 3 % for rice husk. All the unit costs of consumables are values indicted in our study area. They are reported in table 2, section IV. The average salary of each category of workers is based on the real wages observed in the Private Sector in Burkina. The monthly wages for engineer and technician are respectively range of 610 € and 534€. It is 1.25€/h for unskilled employees.

Production cost is calculated on a Levelized Cost of Electricity (LCOE) basis [12] and write as:

$$LCOE = \frac{C_{Cap} + C_{maint} \cdot \sum_{t=1}^{N} (C_{cons} + C_{labor}) \cdot (1+i)^{-t}}{\sum_{t=1}^{N} E_{net} \cdot (1+i)^{-t}} \quad (6)$$

$LCOE$ – Levelized Cost of Electricity (€/kWh); C_{Cap} – Capital cost (€); C_{maint} – maintenance cost (€); C_{Cons} – cost of consumables (€/an); C_{labor} – labor cost (€/year); E_{net} – net electricity output (kWh/year); i – Real discount rate (%). N – Useful life time (year).

The real discount rate is estimated at 9% considering the data provided by the Atlantic Bank of Burkina Faso (case for energy systems based on solar PV) [13]. The useful life time is assuming to be 10 year.

F. Environmental impacts assessment models

The Life Cycle Assessment (LCA) approach was adopted to evaluate the environmental impacts, for a functional unit of 1 kWh of electricity. In accordance with system boundary (only on the biomass conversion system into electricity) the relevant emissions considered concern the air emissions (CO_2, CO, SO_2, NOx , PM) from the combustion of producers gas and chemicals substances from tars (about 35 substances). The inventory data were drawn both from [14], [15], Agricultural Research Centre for International Development (CIRAD) and data based on a mass and energy balance. For the life cycle impact assessment, the ILCD 2011 Midpoint + (V1.08) method was used and the environmental impacts considered are *Greenhouse gas, human toxicity carcinogenic effects, human toxicity non-carcinogenic effects, freshwater ecotoxicity and respiratory effect*. The characterization of any category of impact can be estimated as in equation 7.

$$EI_i = \sum_{s}^{S} FI_s . m_s \quad (7)$$

EI – Category of environmental impact (impact unit/kWh); FI – impact factor of substance s (impact unit/kg); m_s – mass of substance s (kg); S – Number of substances for impact *i*;

G. Social impacts assessment models

For the sake of simplicity due to the lack of reliable data, social impact analysis considers the direct employment generated during the operation of the production system. It is expressed in full-time equivalent jobs (FTE) /year as shown is equation 8.

$$E_{Direct} = \sum_{j}^{J} N_{emp,j} . tw_j \quad (8)$$

E_{Direct} – Number of jobs generated (FTE/year); N_{emp} – Number of employees (person) by category; tw_j – working time of each employee *j* (year).

III- RESULTS AND DISCUSSION

A. Technical performance

1) Overall electricity efficiency

The net electrical energy produced is 318.5 MWh/yr. In figure 2 is presented the hourly overall electricity efficiencies obtain for the two biomasses. The system provides relatively better conversion efficiency with the cotton stalk (between 8 and 18%) than the rice husk (between 7 -17%) under the established conditions. The associated specific biomass consumptions are respectively 1.88 kg/kWh and 2.7kg/kWh. These values are within the range of 1.1 to 1.5 kg/kWh and 1.8 to 3.6 kg/kWh reported by [16] for wood and rice husk.

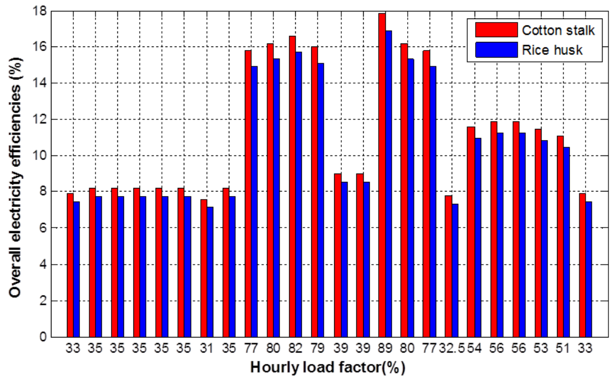


Figure 4: Hourly overall electrical efficiencies

2) System availability

For a mean time between failures (MTBF) estimated at 80 h and mean time to recovery (MTTR) of 24 h, the system availability is calculated at 77%. This is less than the forecast availability of 92% estimated on the operating schedule basis.

B. Economic performance

The estimated capital cost of the production is about 2285,58 €/kWe. With the cotton stalk, the operating cost turns out to be high, either 0.27€/kWh against 0.23€/kWh in the case of the rice husk. The operating cost balances presented in the figure 5 and 6, show that this gap is particularly due to the high labor cost. Therefore, the electricity production cost with the cotton stalk appears higher about 0.38 €/kWh, against 0.34€/kWh for the rice husk.

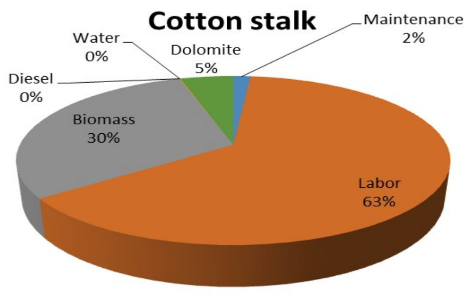


Figure 5: operating cost balances of cotton stalk

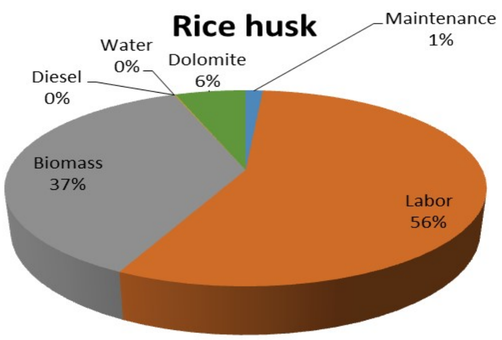


Figure 6: Operating cost balances of rice husk

C. *Environmental impacts*

For the same electricity energy produced, the energy recovery valorization of the two biomasses by the gasification system can allows to avoid 3.06 kg CO2-eq/kWh of fossil fuel emission. In table 2, the results of the others environmental issues are indicated. They show that impact levels of the two biomasses are relatively similar.

Table 2: Environmental impacts of the electricity generation system

Biomass	Environment impacts			
	Human toxicity non cancer effect (CTUh/kWh)	Human toxicity cancer effect (CTUh/kWh)	Freshwater ecotoxicity (CTUe/kWh)	Respiratory effect (gPM2.5/kWh)
Cotton stalk	2.97^{E}-12	4.51^{E}-12	3.73^{E}-03	0,18
Rice husk	3.19^{E}-12	4.72^{E}-12	3.9^{E}-03	0.18

D. *Social impacts*

In terms of jobs creation, the results show that the use of the cotton stalks is most interesting due to the high need for workforce for its cutting, either 9.58 full-time equivalent jobs /year against 8 full-time equivalent jobs /year for the rice husk.

IV- SENSITIVITY ANALYSIS

This sensitivity analysis aims to determine the most influential input variables on the output variables (assessment criteria). The analysis was focused on two assessment criteria that are influenced by at least two input variables: the production cost and the system availability. Two types of sensitivity analysis have been implemented. The first is local sensitivity analysis and has consisted in varying only one variable. The second analysis concerns the global analysis sensitivity where all variables are changed simultaneously. This one is applied only to the production cost.

Thus, to carry out the analysis, we defined for each input variable a range of variation with respect to the basic value used in the above performance analysis. The selected input variables and their variation range are indicated in table 3. These values are determined from reports and expert data.

The sensitivity of generic output variable "*y*" was evaluated as indicated by [17] in the local analysis sensitivity and as described by [18] in the global analysis.

Table 3: Sensitivities input variables

Input variables	Values			
	Unit	Min	Base values	Max
Variables of the production cost				
Moisture of cotton stalk	%	10	15	20
Moisture of rice husk	%	8	12	20
Discount rate	%	3	9	15
Lifespan	Year	5	10	15
Cotton stalk cost	€/t	20	35	50
Rice husk cost	€/t	15	25	30
Water cost	€/m3	0,02	0,78	1.1
Diesel cost	€/l	0,2	1	1.8
Dolomite cost	€/kg	7	9.15	11
Investissement cost multiplier	%	0.7	100	1.3
Variables of the system availability				
Mean time between failures (MTBF)	h	40	80	160
Mean time to recovery (MTTR)	h	2	24	48

A) *Sensitivities of input variables on electricity production cost*

An analysis of the data in the figure 7 for the two biomasses indicates the crucial role of the biomass cost and investment cost on the production cost with high values of the sensitivity. However, the results of the global sensitivity analysis (figure 8) reveals that the production cost was expected to be between 0.2-0.55 € / kWh (mean: 0.35 € / kWh) for the rice husk and 0.25-0.6/kWh (mean: 0.4 €/kWh) for the cotton stalk. The three parameters that showed to have a greater impact on production cost were in decreasing order, the useful lifetime of system (42%), the investment cost (26%), the real discount rate (15%). In the case of cotton stalk, biomass cost appears as the third parameters with 20%.

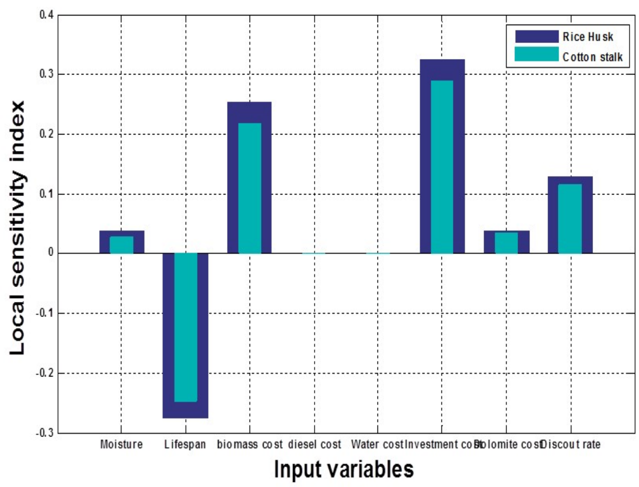
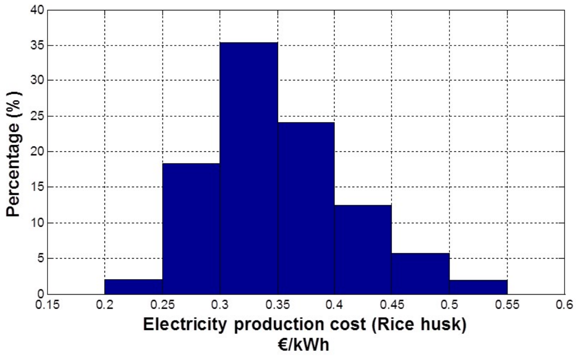


Figure 7: Local sensitivity index on electricity production cost



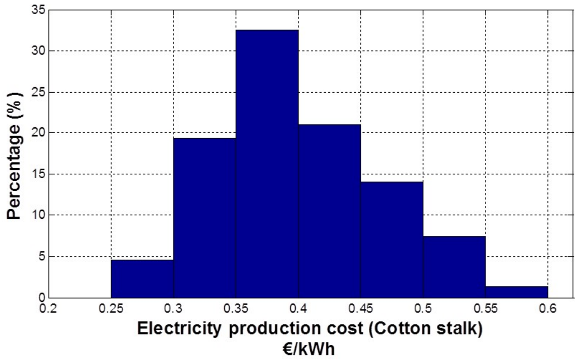


Figure 8: Expected electricity production cost rice husk (top) and cotton stalk (bottom)

B) Sensitivities of input variables on system availability

The results indicate that the availability of the system is more sensitive to the Mean time between failures (MTBF) with a high index of 0.21. The availability of system would decrease between 97- 62% when the mean times to recovery vary from 2 to 48 h. Contrary, it increase from 62-86 % with the variation of the mean time between failures between 40-160h. Hence, it is important that the system would be simple for its easy access, and would be manage with a skilled and experienced workforce in order to minimize repair times and guarantee long -lasting operation.

CONCLUSION

This paper has considered electrification through electricity generated from cotton stalk and rice husk in Burkina. The work proposes a simulation tool for the assessment of both techno-economical and socio-environmental performance applied to a biomass gasification project in Badara village. This approach has allowed estimating the performance criteria in taking into account of the variables related to the local conditions. In general, the study shows that both biomasses offer an interest in terms of energy efficiency. The gasification of cotton stalk generates more expensive electricity than rice husk; but his social benefit in terms of job creation is better. Our approach also has led to identifying the important variables to master such as the useful life time, investment cost, biomass cost.

This work is an important step that could assist the policy makers to make a relevant decision.

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