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A techno-economic Comparison of Biomass Thermo-chemical Systems for Sustainable Electricity in Nigerian rural areas

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Abstract

Biomass thermo-chemical systems (BTCS) source remains one of the means of providing sustainable electricity to rural areas in developing nations. Due the dwindling power generation and supply in Nigeria representing between 10 and 34%, the rural communities are mostly affected in their socio-economic activities. Given the massive biomass resources in Nigerian rural areas, it is feasible to provide sustainable electricity to these communities through BTCS. However, cost has been found to be a major constraint in adopting BTCS. The research works that underpin this paper aim to assess the economics of BTCS in generating sustainable electricity in Nigerian rural areas. Whole Life Costing (WLC) approach has been used to evaluate and optimise various capacities of BTCS. The findings reveal that the cost/kW of system capacities between 150kW to 10kW for combustion and gasification systems, range between US$1427-2,249 and US$1,280-2,489 respectively. The WLC/kWh of generating electricity from the same set of technologies, in order of system capacities above, ranges between US$0.041-US$0.37 and US$0.015-US$0.11. This is considered under 8, 12 and 16 operational hours, without and with Feed-in-Tariff (FIT) incentives. All scenarios evaluated are cost competitive with existing fossil fuel (FF) electricity sources in the country at US$0.13/kWh, except the 50kW combustion system, with and without FIT that exceeds the current electricity tariff in Nigeria.

1 Introduction

Following the failure of the centralised grid system using fossil fuel (FF) sources and inability of the Independent Power Providers (IPP) in Nigeria to generate and supply sufficient electricity, the country has been experiencing power energy shortage for over three decades, despite the country being one of the world's leading exporters of oil and gas and member of OPEC [1,2]. Existing electricity capacity in the country only provides electricity to 34% and 10% of urban centers and rural areas respectively [3, 4]. The current electricity generation capacity is still hovering around the same capacity as at commencement of privatisation in 2005 of 4,000MW for a population of around 170million. Immediate reasons for this problem include persistent energy infrastructures and gas supply facilities vandalism representing over 1,600/annum, as well as high cost of gridline network and weak transmission and distribution facilities [4, 5]. Also, there have been frequent lacks of delivery of generated electricity particularly to far reaching locations due to weakness of transmission and distribution network constituting up to 40% losses [6, 7]. In addition, there is lack of interest in delivering electricity to rural areas by IPPs, due to high cost of grid network extension in relation to their low energy consumption [8].

Rural people, representing two-thirds of the total country's population, are the most affected, as the lack of electricity continues to affect their socio-economic settings [3]. Sambo [8] reported that fuel wood and charcoal (FWC) utilisation has become the main source of their energy and represent over one-third of Nigeria's total primary energy consumption. Also, an average Nigerian rural person lives below US$1.25 [9]; hence, their electricity needs have to be met in sustainable and economical means.

Renewable Energy Technologies (RET) and biomass systems in particular, have been one of the sources of providing sustainable electricity in rural areas in many developing nations. However, given the high cost of RETs vis-à-vis low income of these people, it is fair to conclude that, it is the main challenge in this respect [10].

Garba & Kishk [2] reported on the sustainability assessment of RETs in Nigeria's rural areas based on strength, weakness, opportunity and threat (SWOT) analysis and sustainability indicators, the research concluded that biomass systems are the optimal means of providing sustainable electricity for rural communities. Also, Mahapatra and Dasappa [11] reported on the economic evaluation of biomass, solar PV and grid extension systems. The study concluded that biomass is the most suitable and economical means of providing sustainable electricity to Indian rural areas. Thus, decentralised BTCS may be suitable for alleviating the electricity problems of Nigerian rural areas, given its merits of determining when and where actual electricity is needed. Hence, this paper aims to evaluate the economics of BTCS in generating sustainable electricity in Nigerian rural areas.

2 Biomass energy and Nigeria biomass resources potential

Biomass resources are rural-areas friendly and they are largely found in these communities and include residues from animal, agriculture and forestry, and municipal solid waste [12]. Biomass is capable of being transformed to different forms of energy (electricity, heat and fuel) and can be quickly regenerated in different environments [13]. Biomass is the fourth largest energy source after oil, coal and natural gas. By the end of 2014 bio-power global capacity was around 93 Giga watt (GW) and 75% of electricity generated from biomass was from solid biomass fuel, biogas (17%), MSW (7%) and biofuel (1%). Also, during the same period approximately 2% of the total global electricity was generated through bio-power systems [14].

Dasappa [7] estimated Nigerian biomass resources of around 30% forest and agricultural residues availability, to be capable of resulting in a 15,000MW power generation capacity. While ECN [1] projected Nigeria's biomass resources consumption per annum to be around 144 million tonnes. Biomass perhaps can generate up to 68,000 GWh per annum using only one-third of its resources availability for the country's rural communities [2]. Given all of the above, biomass resources can be used to provide sustainable electricity in Nigerian rural areas without a supply chain issue. However, IRENA [12] suggested that biomass supply chain should be given emphasis before adoption in these communities as this determines biomass electricity tariff.

3 Biomass energy conversion systems

Biomass systems are mainly classified into two and include thermo-chemical (combustion, gasification and pyrolysis) and biological (biogas) systems. Given that this study is aiming to provide sustainable electricity to rural areas, only technologies that are commercially available, with experience of utilisation will be used. Thermo-chemical systems (TCS) have been selected for evaluation in this study. Also, only gasification and combustion systems are commercially available among TCS [15].

Direct Combustion (DC) converts biomass materials to heat and electricity through production of steam in a boiler and uses this to drive steam turbines for electricity generation [16]. Miguez [17] DC system classification based on system capacity include: fixed bed (less than 40kW), moving grate (between 40-150kW) and retort system (greater than 150kW). For the purpose of this study, (maximum capacity of 150KW) both fixed bed and moving bed grate have been selected for evaluation.

Gasification system (GAS) converts biomass through partial oxidation into a gaseous mixture of syngas/product [18]. The producer gas (PG) is of low caloric value containing about 4-6 MJ/kg compared to natural gas having 35-50 MJ/kg due to a high nitrogen presence in excess of 50%. Currently, the electricity generation from a small scale GAS plant is mainly via Internal Combustion Engines (ICE) [19]. GAS is classified into fixed bed, fluidised bed and entrained flow gasifier. Considering the low energy utilisation of rural communities only the downdraft -fixed bed gasifier is suitable for small scale power generation ranging from 10 kW to over 100 kW and has been fully commercialised [12].

4 Methodology

This study aims to evaluate the economics of biomass thermo-chemical systems (BTCS) in providing sustainable electricity in Nigerian rural areas. To achieve the aim of the study, Whole life costing (WLC) techniques has been used. The justification for its use is that it systematically sums up the whole cost and revenue related to the asset, from the commencement stage through the operation to the end of the asset. This allows for determining the unit cost of electricity from an energy source. Also, it can optimize cost of ownership and running of physical assets by representing their present worth value. Furthermore, WLC helps in making the right decisions at the beginning or during the operation of the asset. However, it has been criticised for not taking into account returns and benefits of investment [20].

The WLC framework proposed by [11] has been adapted and modified for use in this study, as it can accommodate RETs incentives strategy and energy systems that require continuous fuel utilization such as biomass resources. The feed-in-tariff incentives utilised in Nigeria has replaced carbon trading incentive in this framework as it is still under legislation in Nigerian. See details in table 1. Salvage value and inflation are not considered in this study for ease in decision making. The WLC framework is given by:

$$WLC = \frac{C_G + C_E + (C_F + C_M) \times P(d,n) + C_R \times P(d,n_1) - FIT \times P(d,n)}{L \times h \times n} \quad (1)$$

•Where CF= (SC x fcon x h x fC), CM = (SC x f x MC), FIT = (L x h x n x I)

CG is capital cost of primary converter (PC), CE is capital cost of engine/generator, CF is annual fuel cost, CM is annual maintenance cost, SC is PC rating (kg), fcon is fuel consumption (kg/h), fC is unit fuel cost, MC is maintenance cost of the system, P is present worth factor, d is discount rate, n is life of the project, n1is life of each component, CR is component replacement cost, FIT is annual feed-in-tariff benefit, I is incentive benefit, h is annual operation hours, L is load (kW).

Wood biomass has been used for this study because of its strategic benefits such as high LHV (high-energy content), lowest ash content, acceptable humidity, cost competitive, largely available in Nigerian rural areas context and suitability for both downdraft gasification and stoke grate boiler DC. Its price has been obtained from field survey. The resource persons were interviewed, the weights of the wood was measured, and the prices obtained were then converted to cost/tonne. The total price of the supply chain, including transportation, is US$112.50 representing 45 units as classified in the market, which constitute 105kg/unit. Each unit is sold at US$3.00. Hence, the unit cost of the wooden fuel is N5710/ton (US$28.60). This principle has been adopted for other fuel sources, such as cereal straw US$30.00/ton and rice husk US$62.50/ton; even though they are not used in this study. The low-price of wooden biomass may be connected to the fact that its market has already been established without supply chain problem. The biomass fuel consumption figure utilised reflects averages reported in the literature and as obtained from manufacturers. See table 2 for details.

The costs of BTCS conversion components have been sourced from the manufacturers directly. This is because existing literature reported widely varying figures; these did not change in this context as variations are because of, size, location and technology maturity. While GAS is an emerging technology, location factors (more expensive in Europe and America but cheaper in India) has been emphasised by the study of [21] and [22]; and Ganesh and Banerjee [23] confirmed that "gasifiers cost in India is much lower than those elsewhere". DC components prices are the most stable because the system has been utilised for a long period of time [14]. The capacities proposed in this study are for rural areas application not exceeding 150 kW.

The costs of BTCS conversion components, their accessories and installation figures are presented in table 3. All the costs obtained have been converted to US dollar, while the costs for gasification and DC systems have been respectively obtained from India (Rupees) and China (Yuan). Details of other parameters such as fuel consumption of the conversion systems, together with their life span, engine replacement, energy utilised, discount rate (from Nigerian central bank) and maintenance cost [11] are presented in table 2. Also, *the exchange rate of 200 Nigerian Naira to one US dollar is used.*

	2012	2013	2014	2015	2016
SHP	23.56	25.43	27.46	29.64	32
Wind	24.54	26.51	28.64	30.94	33.43
Solar	67.92	73.3	79.12	85.4	92.19
Biomass	27.43	29.62	32	34.57	37.36

Table 1: FIT Model in Nigeria (Whole Contract Prices N/kwh) (NERC 2013)

Factors	Combustion	Gasification
Biomass Technology Cost (US$/KW)	1,427 -2,247	1,280 - 2,470
Fuel Consumption/Kw (kg/hr)	Wood-50kw -8.6 wood-100kw-5.4, wood-150kw -4.30	Across all capacities (Wood - 1.4)
Life span of Primary Conversion system	Boiler -25 yrs	Gasifier - 15 years
Life span of secondary conversion system	ST -25 years	ICE - 7.5 years
Energy Consumption	Fixed -36kW	20% -syst cap
Engine replacement	NA	1
Discount Rate	13%	13%
Annual Maintenance cost (US$/ kW)	0.024	0.024

Table 2: The Parameters Utilised

5 Data Analysis and Discussion

The investment cost and unit tariff of electricity from BTCS systems are presented in the subsequent sections.

5.1 BTCS investment cost in Nigerian rural areas

The cost/kW of direct combustion (DC) and gasification system (GAS) are presented in table. The findings depict that the capital cost/kW for DC and GAS respectively ranges between US$ 1427 -US$2,247 and US$ 1280 – US$2489. Also, GAS is more economical than DC system despite its existence for long period of time, and being more utilised, representing approximately 75% of total electricity generated from biomass systems [14]. The findings agree with studies by [12] and [22]. The economy of scale noticed in this study, is indicative that the higher the BETs capacities, the lower the cost/kW. This is in agreement with Siewert et al. [24] that higher capacity plants have better economy than smaller plants.

Table 3 also reveals the cost structure associated with BTCS. The conversion systems together with their associated fittings and accessories account for approximately 91% of the total investment cost for both DC and GAS. While other cost factors such as civil and electrical works make up the balance. Similarly, the primary conversion systems (gasifiers, and boilers) account for around 35% and 59% of the total investment cost for both DC and GAS respectively; while generators (secondary conversion systems) represent average of 56% for DC and 32% for GAS. These findings agree with IRENA [12] that "The converter system usually accounts for the largest share of capital costs". However, the findings disagree with Macdonald [25] that the percentage contribution of the generator to the overall investment cost ranges between 5% and 15%. The difference between this research and Macdonald [25] is that, this study focuses on small scale capacities (kW), while his study was on large scale capacities (many MW). Hence, economies of scale have significant impact in reducing unit cost of a system. The reason for high cost structure of conversion systems in this context is associated with the automated and mobile concept adopted; as well as limited civil structure and interconnectivity of electrical services and less labour utilisation during operation given the location of the usage (rural areas). The steam turbine generator under DC has high cost than even the boiler in this context. This is because the steam turbine is a well-proven technology globally, and can last for expected life cycle of the system. That is why both the literature and manufacturers do not suggest its replacement during the life cycle of the system. This is in agreement with Gonzalez et al. [15] that steam turbine "is a well-proven and mature technology with high level of deployment------- and the main advantage of STs is their high time availability". Hence, the capital cost/KW identified in this study particular for 100 kW and above are cheaper than some of the FF electricity plants recently built in Nigeria.

5.2 Unit cost of BTCS electricity in Nigerian rural areas

Figure 1 reveals typically the WLC/kWh of generating from DC system. In this figure, 3 system capacities and 3 different operational hours have been considered. The findings show that both 100kW and 150kW scenarios have WLC/kWh ranging from US$ 0.068 – US$0.11 without incentive; while with FIT the prices reduce significantly to US$0.041 – US$0.08. Also, both scenarios are competitive with the current electricity tariff in the country using FF options (US$ 0.13/kWh). However, none of the 3 operational hours, with and without FIT of 50 Kw is economical with current electricity tariff in Nigeria. This is because the WLC/kWh ranges between US$0.30 and US$0.37. This cost range is significantly higher by over 100%. Also, even the usage of incentive in this case does not have impact in any way.

Direct Combustion				**Gasification**						
Boiler				**Gasifier**						
Capacity (kW)	**50**	**100**	**150**	Capacity (kW)	**125**	**100**	**50**	**32**	**24**	**10**
Boiler Plant	32,525	32,937	57,115	Gasifier and accessories, chiller, wood cutter, dryer	95,067	79,317	41,202	27,657	20580	14,301
Accessories and Fitting	12,500	13,200	13,200							
Cost of Boiler & accessories	**45,025**	**46,137**	**70,315**	**Cost of gasifier & accessories**	**95,067**	**79,317**	**41,202**	**27,657**	**20,580**	**14,301**
Steam turbine				**ICE**						
Steam turbine and accessories	57,377	81,967	127,868	Gas Engine & accessories	53,433	44,183	21,798	14443	11920	6,599
Cost of steam turbine & accessories	**57,377**	**81,967**	**127,868**	**Cost of ICE & accessories**	**53,433**	**44,183**	**21,798**	**14,443**	**11,920**	**6,599**
Total cost of boiler & turbine	**102,402**	**128,104**	**198,183**	**Total cost of gasifier & ICE**	**148,500**	**123,500**	**63,000**	**42,100**	**32,500**	**20,900**
Others				**Others**						
Installation + commissioning	2,500	2,500	3,000	Installation + commissioning	1,500	1,500	1,000	1,000	1,000	1,000
Civil works	2,000	2,000	2500	Civil works	2,000	2,000	1,500	1,500	1,500	1,500
Earthing work	350	400	400	Earthing work	400	400	300	300	300	300
Price & Design Risk (5%)	5,120	6,405	9,909	Price & Design Risk (5%)	7,620	6,370	3,290	2,245	1,765	1,185
Total cost of the system	**112,372**	**139,409**	**213,992**	**Total cost of the system**	**160,020**	**133,770**	**69,090**	**47,145**	**37,065**	**24,885**
Cost/kW (US $)	**2,247**	**1,394**	**1,427**	**Cost/Kw (US $)**	**1,280**	**1,338**	**1,382**	**1,473**	**1,544**	**2,489**

Table 3: The Cost/kW of BETs systems in Nigeria's Rural Areas

The electricity consumption under all of DC system in this case is fixed (36KW) as highlighted in table 2 and has significantly impacted on these scenarios, particularly 50 kW. Typically, 50kW minus 36kW, the owner/investor has been left with only 14kW capacity electricity. But as you go higher the efficiency increases. This is in agreement with Demirbas [26] that "higher efficiencies are obtained with system of many MW". More so, the fuel consumption of the 50kW scenario is the highest among all the BETs and system capacities considered in this study, with over 8kg/Kw.

In the case of GAS, 6 scenarios have been considered, and for each 3 operational hours are utilised. The WLC/kWh for generating electricity under GAS (125KW – 10kW) with FIT is between US$0.015 – US$0.07, while without FIT is between US$0.05 – 0.11. Under GAS none of its system capacities exceed the current electricity tariff in the country using FF (US$0.13). These findings are in agreement with [4], Mahapatra and Dasappa [11] and Dasappa [7] that biomass sources are cost competitive with FF sources in generating electricity particularly in developing countries. However, they disagree with Evans et al. [13] that "biomass power production is not cost effective at present". Hence all the BTCS system capacities considered in this context are cost competitive with FF source at present and suitable for providing sustainable electricity in the country's rural areas even without incentive, other than for a DC system with 50kW capacity.

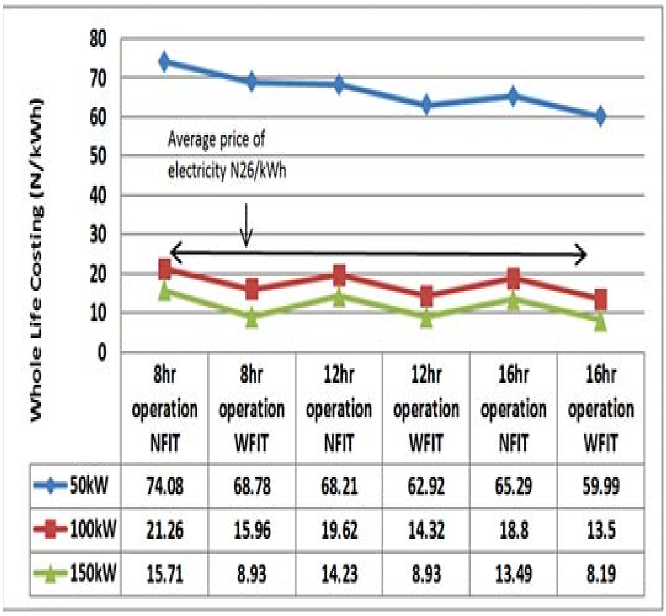

Figure 1: WLC/kWh of Direct Combustion systems in Nigerian Rural Areas.

6 Conclusion

Following the dwindling power energy generation and supply in Nigerian rural areas resulting from the high cost of gridline network and perennial vandalism of energy infrastructure in the country reflects that there is the need for adoption of sustainable and economical ways of electricity provision. Decentralised BTCS has been identified as the most suitable means of electricity provision in these communities given vast biomass resources availability in relation to their low energy consumption. All the BTCS capacities considered in this context are cost competitive and suitable for providing sustainable electricity in these communities even without incentive except DC (50kW). The capital cost/kW of DC and GAS represents US$ 1427 -US$2,247 and US$ 1280 – US$2489 respectively. However, this study is recommending utilisation of a FIT incentive strategy as it will guarantee the participation of private investors (IPPs) in these communities given the lack of any energy infrastructure. More so, the FIT incentive utilised in this context is just an indicative as shown in table 1, hence its utilisation should be extended to decentralised energy systems not restricted to only grid systems. Further work includes the development of a framework for sustainable electricity provision in Nigerian rural areas.

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