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Evaluation of CHP for Electricity and Drying of Agricultural Products in a Nigerian Rural Community

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Abstract

The techno-economic performance analysis of biogas production, power generation and recovery of heat for drying of agricultural products for a Nigerian rural community is explored through process simulation. In this work, biogas generation from a 10.33MT/day cattle market waste was fed into a 72kW$_e$ CAT internal combustion engine and the model has been developed using Aspen HYSYS^R process simulator. Simulation results shows that about 191.63MT per annum of tomato can be dried with the recovered heat while heat recovery for anaerobic digestion and drying of agricultural products increases the system's heat efficiency from 25.6% to 58.4%. The results also show that, with the current electricity tariffs for remote areas being charged at USD 0.02/kWh and Feed-in Tariffs (FITs), NPV is positive and the payback period is 3.2 years. However, system less than 1MW is not currently captured in Nigeria's FITs system while the economic indices are negative without FITs. Effects of interest rate regimes on economic indices is also explored as such system could be farm based and entitled to loan from the Nigerian Agricultural Development Bank, Bank of Industry and Commercial banks with interest rates 7%, 9% and 20% respectively. The results presented in this paper increased research knowledge on application of biogas CHP in Nigerian rural communities especially on integration of energy generation with processing of agricultural products

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CHP, electricity, drying, agricultural, products, biogas

1.0 Introduction

Sub Saharan African (SSA) countries is reported to have the greatest percentage of the global energy poor and the retardation of its economic growth is strongly linked to inadequate electricity infrastructure [1;2]. Nigeria, a SSA country, has one of the global electricity challenge. The national grid connection is only 46% while over 96 million citizens have no access to electricity [2][3] At the moment, ineffective generation, distribution and supply network coupled with an ineffective institutional framework and lack of appropriate policies has led to supply deficit [4]. Apart from incessant breakage of pipelines that disrupt gas supply to the 11 thermal plants, seasonal drying of dams also affects performance of the 3 hydro plants. Thus, generation barely exceed 4000MW from 8039MW installed [3].

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Therefore, decentralised off-grid renewable energy systems can go a long way in sorting Nigeria's energy challenge [5]. Since 1999 government policies have focused more on boosting of agricultural production via soft loans and provision of farm tools to farmers without making any provision for the processing and storage of agricultural products which has led to increased post-harvest loss [6]. At the moment, approximately 45% of food produce is been wasted during distribution and consumption and could be as high as 90% depending on the produce and seasons [7][8]

For instance, Nigeria is the second largest producer of tomato in Africa with about 1.5 million metric tons produced in 2011, 60% of which got wasted. Therefore, about 300,000 tons was imported to meet up with 1.2 million metric tons local demand. Importantly, distress sales of agricultural products is very common in most Nigerian rural communities. Rain fed agriculture is the predominant practice [8]. Therefore, crops are planted, matured and harvested at the same time which lead to flooding of local markets with the crops and farmers are forced to sell at ridiculous prices with miserable financial return.

Aspen Hysys is a simulation tools that can be used to predict thermodynamics properties and behaviour of hydrocarbon and chemical systems [9]. Supplying necessary thermodynamic data, accurate operating conditions, and required equipment models, plant's behaviour can be simulated including its sensitivity analysis. Hence, it is employed in this work. Importantly, the essence of this work is to examine feasibility of off-grid combined power and drying system in Nigerians rural communities in context of the current renewable energy policies of Nigerian government.

2.0 Materials and Methods

The methods used in this work involves field work, data collection and analysis of a local cattle market waste. Given the nature of the waste: an anaerobic digestion system is proposed. Thus, the approach involves: ultimate analysis of the waste sample, evaluation of potential biogas production through anaerobic digestion, selection of digester, engine generator, dryer and computational simulation of the process using Aspen Hysys. Finally, an economic evaluation of the potential utilisation of the cattle market waste for electricity generation and drying of agricultural products is presented.

2.1 Study area

Igbo-ora, is an agrarian rural community in Oyo state South-western part of Nigeria. The population as at 2013 is 64,431 with about 440km^2 landmass. Its geographical coordinates are (7° 26' 0" North; 3° 17' 0" East). Daily temperature ranges between 20^{0}C and 35^{0}C with 28.5^{0}C being the annual average. Its annual rainfall is above 1000mm while humidity is also very high at about 70% annual average. Igbo-ora is a market community where agricultural products are sold every 5th day and lots of market waste mainly vegetables are generated on market days. Animal waste mainly cattle dung with leftover grasses is equally generated at the cattle market (Figure 1a).

1a 1b

Figure 1: Cattle feeding stall in the market and weighing of waste.

2.2. Daily waste generated in the market.

Cleaning is done weekly. So Quadratic sampling was used for the estimation of cattle in the market and the selected quadrats were cleaned and the generated waste, presented in Table 1was measured with a weighing balance (Model: Hana, China) shown in Figure 1b.

2.3 Waste characterisation and determination of methane generation potential

Characterisation of the waste into its compositional percentage was done using the method adopted by [10] and [11]. Thus, as in the waste quantification, it will be challenging to sort all the waste. So, as quantification was on-going, every 15^{th} head-pan was sorted and the quantities of organic waste, plastic bags, plastic bottles, paper, woods, textiles and other foreign materials were determined using weighing balance. The overall wet weight of different component was evaluated, expressed in kilogram and then stated in percentage as shown it the Table 2. Using AOAC analytical methods [12] for proximate and ultimate analysis of the cattle market waste, the moisture content, total volatile content and fixed carbon were determined. The proportion of chemical elements: Carbon (C), Hydrogen (H), Oxygen (O), Sulphur (S) and Nitrogen (N) were determined. Table 3 shows proximate and ultimate analysis of the waste.

Table 1: Daily waste generation in the market.

Particulars	Quantity
Cleaning frequency	weekly
Size of quadrat	18.3*36.6m^2
Number of quadrat per acre	12
Number of quadrats in 3 acres	36
Number of pans per quadrats	245
Average weight per pan	8.2Kg
Weekly waste per quadrat	2009Kg
Daily waste per quadrat	287Kg
Daily cattle waste generated in the market	10,332Kg

Table 2: Characterisation of the waste.

Particulars	Quantity (%)
Organic waste	98.4
Plastic bags	0.8
Plastic bottles	0.4
Woods	0.2
Paper	0.1
Textiles	0.05
Others	0.05

Table 3: Proximate and ultimate analysis of the waste.

Proximate analysis		Ultimate analysis	
Constituent	%	Constituent	%
Moisture content (wet basis)	45.05	Carbon	40.73
Total solids	55.04	Hydrogen	5.17
Volatile solids	60.3	Oxygen	31.47
Ash content	19.15	Nitrogen	2.87
		Sulphur	0.61

2.4 Theoretical determination of biogas and energy yield

The elemental percentage composition of the waste is known. Therefore, using Buswell equation (1) the empirical formula and theoretical biogas generation is evaluated [13].

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2 \rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + nH_2S \quad (1)$$

The empirical formula is $C_{178}H_{271}O_{103}N_{11}S_1$. However, Buswell equation assumes 100% biodegradability [14] of carbon whereas in practice degradability is less than 100% and it is substrate specific. Hence, 70% conversion is assumed for cow dung. Thus, about 872.09Kg/day of methane can be obtained from 10,332Kg being generated daily in the market.

2.5 Digester and Dryer

Based on the nature, quantity of the waste and agricultural produce considered, the features of the digester and dryer used is presented in Table 4. Atesta dryer is chosen for its simplicity, ease of maintenance and popularity in the Sub-Saharan African region [12].

Table 4: Features of dryer and digester used

Digester		**Dryer**	
Digester type	Continuous stir	Name	Atesta gas dryer
HRT Days	20	Energy source	Propane
Total solids used	10%	Consumption	0.5kg/hr
Reactor volume	1291.5m^3	Capacity	100kg/cycle
Reactor area	688.53m^2	No of trays	20
Feed density	1040kg/m^3	Tray unit area	0.84m2
Specific heat of feed	4.18kJ/kg/^{0}C	Drying time	24hrs
		Cost (€/m2 of tray)	182
		Operating temperature	60-90C
		Suitability	Mango, tomatoes

2.6 The system design of the combined power and drying system.

The system is shown in the Figure 2. The market waste was sorted, crushed and mixed with water in the treatment tank, diluted to required total solids and raised to the digestion temperature. The conditioned waste is anaerobically digested under mesophilic conditions and the biogas produced is pumped through ferric oxide and calcium hydroxide solution columns. The treated biogas is then burnt in a reciprocating internal combustion engine to produce electricity. Heat is recovered through jacket water to maintain the digestion system while the recovered heat from the engine exhaust is used for drying of farm products.

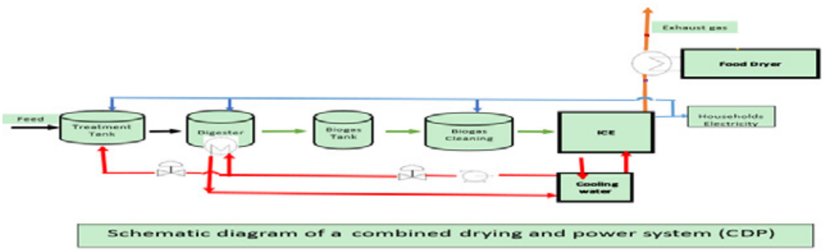

Figure 2: Combined drying and power system

2.7 Process Simulation

Using technical data of a 72KWe biogas driven CAT gas engine Aspen HYSYS^R software was used to simulate and predict electricity and heat generation of the engine Figure 2. Aspen HYSYS^R can be used for an accurate prediction of thermodynamic behaviour of chemical and hydrocarbon systems [15]. The model is based on blocks corresponding to unit operations as well as chemical reactions such as compression, expansion and combustion. A complete process could be built by connecting the blocks with materials streams such as heat and work streams. The user needs to supply:

a) Flow rates, compositions and operating conditions of the inlet streams.

b) Operating conditions of the blocks used in the process, e.g. temperature and pressure.

c) Operating heat and/or work inputs into the process.

d) The appropriate fluid package for the thermodynamic properties of the system.

Once these are supplied, Aspen calculates the output streams' flow rates, compositions and conditions. In this work, Peng-Robinson equation of state is used as the property package as it is able to predict thermodynamic behaviour of gases at high temperature [9][15].

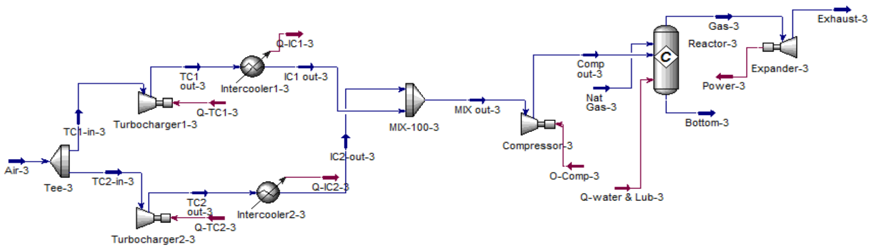

Figure 3: Cat engine simulation in Aspen HYSYS^R.

Using 67% methane purity of the fuel, at 100% load, the result of simulation is presented in Table 5.

Table 5: Simulation result.

Particulars	Specification	Simulation	Deviation (%)
Power (kW)	72	72.93	+1.3
Combustion air flowrate (m^3/h)	292	291.9	+0.04
Exhaust stack gas temperature (C)	581	587.2	+1.07
Exhaust gas flowrate (m^3/h)	324	334	+3.1
Heat rejection to water jacket and lubricant (kW)	-115	-115.1	+0.87

3.0 Drying of agricultural produce: tomato

The model proposes replacing propane gas burner in the dryer with the recovered heat from the CAT engine's exhaust.

Heat supplied Q_P (kJ/h) by propane is $QP = \dot{m}. (LHV)_P$ (2)

Where ṁ and $(LHV)_P$ are mass flowrate and low calorific value of propane (46300kJ/Kg) respectively. Thus, Q_P is 23,150kJ/h

Recoverable heat from exhaust Q_E at 200^{0}C stalk temperature is calculated as 165,252kJ/h at 80% heat exchanger efficiency. Hence, about 7 propane driven Atesta dryers can be driven with the exhaust gas of the plant. Assuming, 90% plant availability and 24hour drying time per cycle for tomato. Then, 9581.25Kg/annum of tomato can be dried.

4.0: Heat Recovering for Digestion

Considering the nature of the waste, a cylindrical concrete mould continuous stirred tank reactor (CSTR) is considered in the study. The reactor size (Vr) was calculated based on feedstock characterisation in Table 3 and the total solid (TS) was assumed to be 10% while 20days was used as the hydraulic retention days

(HRT). The specific heat of the feed was assumed to be that of water 4.18kJ/kg/^{0}C while the feed density was set at 1040kg/m^3 [16]

Digester volume (Vr) = SD*HRT (m3 = m3/day* number of days) (3)

Where SD is the daily substrate input. The required TS is 10%, therefore from Table 3, the ratio of substrate to water is 1:5.5. This brings the daily substrate input and reactor volume to 67,158kg/day and 1291.5m^3 respectively. According to [17], ratio of height to diameter of 2:1 is considered moderate and the calculated area of reactor is 688.53m^2. The digester is operated at mesophilic temperature of 35^{o}C and recovered heat from water jacket and lubricant oil was used for the process. The engine used low grade biogas about 67% methane. Hence, no rigorous upgrading is considered. The biogas is only pumped through ferric oxide and calcium hydroxide solution columns which is considered enough to give the required biogas quality.
However, heat required for digestion is the heat needed to raise the temperature of feedstock from ambient temperature (25^0) to digestion temperature (35^{0}C) plus heat needed to maintain the temperature (heat loss) Castellanos et al. [16]. Hence,

$$HT = HL + HF \quad [kW] \qquad (4)$$

Where HT is the total heat demanded for digestion while HF and HL are heat requirements for digestion and heat loss respectively.
According to [16], HL and HF can be obtained from equations 5

$$HF= \dot{m}.C.r\ (T_{op}-T_{ab}) \quad [kW] \qquad (5)$$

Where C is the specific heat capacity of feedstock [kJKg $^{-1}$^{0}C^{-1}], ṁ is the volumetric flowrate of feedstock [m^3/s], r is the feedstock density [kgm-^{3}], T_{op} and T_{ab} are digestion and ambient temperatures [^{0}C] respectively. Hence, HF= 32.49kw.
Using height to diameter ratio of 2 as suggested by [18][17] and heat transfer coefficient U [0.002kW m-^{2}^{0}C-^{1}] is for concrete block, HL can be evaluated from equation 6

$$HL=UA\ (T_{op}-T_{ab}) \quad [kW] \qquad (6)$$

Hence, from equation 6, HL is 13.771kW and the total heat required for digestion is 166538.6KJ/h. Thus, the total heat recovered from the system for drying and digestion is 331790.6KJ/h.

5.0 Economic Analysis

The investment and operating cost for the system is drawn from the Nigeria's National Electricity Regulation Commission [19] for biomass based electricity generation. However, the cost of dryer is calculated differently. Assuming 20 years life span of the plant and 90% availability. Therefore, the plant will generate 567,648kWh per year and 11,353MWh in its lifespan 10% of which is used onsite (Ibid). Hence, 56765kWh is sold off-site. The viability of the project is accessed using levelized cost of electricity (LCOE), Net Present Value (NPV) and Payback period (PP) analysis as described by Short et al[15]. Input for the economic analysis and the project is presented in Table 6.

Table 6: Input for the economic analysis and the project cost

Economic Analysis			**Project's cost**	
Parameter	Unit	Amount	AD unit	Dryer
Capital cost	$/kW	2900	208, 500	3471.32
Fixed O&M	$/kW/yr.	53.5	77,040	
Variable O&M	$/MWh	0.95	10,785	
Fuel cost	$/MWh	5	56,765	
Parasitic load	%	10		
Life Span	Yr.	20		
Interest rates	%	7,9,20		
Capacity	kW	72		
Availability	%	90		
Dryer	Kg(wet)	191,625		
Replacement (60000h)	$	$1000/kW	189,216	9122.63
	TOTAL		**554,899.95**	

Thus, using the above figures in Table 6 and \$ 0.111/Kg and \$3.5/Kg as local prices of wet (95%MC) and dried tomatoes (8%MC) respectively, the economic performance at 7% interest rate with and without FITs is presented in Table 7 while performance at different obtainable interest rate is shown in Table 8.

Table 7: Effect of electricity price and FITs on the system.

Consumers	Electricity prices (\$/kWh)	NPV@ r =7%	Payback Period (Yr.)
Rural (R1)	0.0200	-318316.67	>20
Sub urban (R2)	0.0897	46622.85	17
With FIT	0.1868	572,238.83	3.2

As shown in Table 7, the system is, without FITs, only economically feasible for semi-urban regions classified as R2 by the Nigerian Electricity Regulation Commission with the current tariffs of USD\$0.0897/kWh. Though, its feasibility in this regards is subject to the interest rate regimes. Being farm based, such systems are entitled to loan from the Nigerian Agricultural Development Bank, Bank of Industry and Commercial banks with the interest rates 7%, 9% and 20% respectively. At these interest rates, the Levelized Cost of Energy are \$0.082, \$0.090 and \$0.141/kWh respectively. Besides, while NPVs of \$46,622.85 and 15,259.89 were obtained for 7% and 9% interest rates, the NPV is negative at 20% interest rate Table 8. The payback periods are rather too long, 17, 19 and above 30 years respectively. Importantly, systems less than 1MW are not currently included in the Feed in Tariffs. With FITs such systems have a positive NPV even at 20% interest rates.

Table 8: Economic performance at different interest rate.

Interest rate (%)	NPV (USD\$)	LCOE (\$/kWh)	Payback Period (Yr.)
7%	46622.85	0.082	17
9%	15259.89	0.090	19
20%	-81637.85	0.141	>20

6.0. Conclusion

The results indicate that heat recovery for drying and digestion increases the system efficiency from 25.6% to 58.4%. However, such system is not economically feasible with the current electricity retailing price of \$0.02/kWh in the rural area as all economic indices are negative. Nevertheless, such a system is, subject to interest rates, promising in the suburban regions of the country. Inclusion of small scale renewable energy systems in the Nigeria's Feed-In-Tariffs is therefore recommended as economic indices show such a system to be profitable regardless of the current interest rates of commercial banks.

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Biography

Rasaq Oladiti Lamidi holds a masters degree in Carbon and Resources Management. He has worked in food and beverage industries for a decade. He is currently a PhD student in Energy at the School of Mechanical and Systems Engineering, Newcastle University where he is working on sustainable synchronization of rural energy with food processinng.