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Off-grid electricity generation in Nigeria based on rice husk gasification technology

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ABSTRACT

Nigeria is purely an agrarian nation and the people depend on agriculture for survival. One of the missing links to wealth creation in Nigeria is lack of economic exploitation of abundant agricultural wastes. Instead of wealth creation, rice husk has become a serious threat to the environment. The unutilized rice husks in rice mills in Nigeria generate millions of tons of $C0_2$ when burnt. This increases environmental degradation and deaths associated with respiratory diseases. The sustainable use of this rice husk for bioenergy applications such as electricity generation at low cost, to mitigate greenhouse gas emissions is imperative. In this paper, an off-grid gasification power supply option for Adani, in Uzo-Uwani Local Government Area of Enugu state, of eastern Nigeria is presented. A detailed load assessment and availability of rice husk for power generation in the study area was conducted. This information was used to design the gasification system. The gasification system was designed based on the mass flow rate of producer gas required to power the gas engine at full load. The gasifier was designed downdraft with air and steam as the oxidizing agent, in order to maintain uniform temperature in the oxidation and reduction zones. Furthermore, techno-economic analysis approach was used to determine the economic viability of the designed power system considered in this study. The estimated total load demand of the study area is 850.054 kW. The estimated total daily, monthly and yearly energy demands of the study area are: 8,991 kWh, 269,736.42 kWh and 3,236,837.04 kWh. The annual availability of rice husk in the study area is $3,636\ t/y$ and it has potential of 1.52 MW power generation with daily, monthly and yearly energy generation of: 36.48 MWh, 1,094.4 MWh and 13,132.8 MWh. This potential of electricity generation has power station capacity of 1.9 MVA, which is approximately equal to 2 MVA. The Levelized Cost of Electricity of the designed power system is 3.6 Naira/kWh, which is cheaper than 30.93 Naira/kWh tariff bill by Enugu Electricity Distribution Company to its R2S customers. Based on the proposed rice husk gasification system, a community could generate power to meet their electricity demand in most economical way, thereby reducing emission, waste and saving cost translating to sustainable development.

1. Introduction

The bedrock of development of any nation is electricity. Access to electricity could transform the lives of people, communities and nations. Presently, over 1.3 billion people around the world are yet to have access to constant electricity supply (International Energy Agency Report, 2014). In Sub-Saharan Africa (SSA), 585 million people have no access to electricity, including Nigeria, with a share of 76.6 million persons (Mandelli et al., 2015), been the most populous country in the continent. About 65% of these people without access to electricity in Nigeria live in rural or isolated areas; most have scant prospects of gaining access to electricity in the near future (Akpan and Udoakah, 2013).This is because

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of the epileptic nature of the Nigerian power grid, which makes grid extension hard to implement. According to International Energy Agency projections, by 2030, the number of people without access to electricity in rural areas is not likely to decrease because of population growth (United States Agency for International Development, 2014). The lack of electricity supply in rural or isolated locations of Nigeria, stands as an obstacle in achieving the Millennium Development Goals (MDGs) (Meisen and Akin, 2008). For instance, to achieve universal primary education, educational facilities need electricity for teaching aids and good lighting for reading at homes; to reduce child mortality and improve maternal health, health facilities need refrigerators to preserve drugs/vaccines and proper lighting for effective service delivery; to enhance internet and communication access, telecommunication networks needs electricity to power the network. This shows that there is a high correlation between electricity consumption and human development index in low income countries.

Nigeria is currently undergoing industrial evolution that is met with many constraints. The key constraint to the industrial evolution is unreliable power supply which is as a result of over reliance in petrol, diesel and hydro sources of energies for electricity generation (Ohajianya et al., 2014). In Nigeria, hydro and fossil fuel are the chief sources of energy for power generation (Sambo et al., 2010). But during dry season, hydro source of energy is affected as the head of water decreases noticeably, leading to a direct decrease in the output power, as presented in reference (Uhunmwangho et al., 2018) for the comparative analysis of different mini hydro turbines. For thermal plants, they are affected by government policies because government controls the price of petrol and diesel. Again, petrol and diesel are not economical to produce and they release greenhouse gas during operation. The greenhouse gas leads to death associated with respiratory diseases. Based on this, reference (Uhunmwangho and Okedu, 2009) proposed macro and mini hydro power plants as an option for social economic development.

The buck of electricity generation in Nigeria comes from national grid, and grid extension still remains the preferred mode of rural electrification (Oyejide et al., 2014). However, the extension of national grid to geographically remote and sparsely populated rural areas can either be financially unviable or practically infeasible. Off-grid power options like renewable and clean energy system can be helpful in such cases, as presented in reference (Okedu et al., 2015), considering the challenges and opportunities they may offer. In Nigeria, the efforts for off-grid electrifications have focused on solar photovoltaic and wind energy systems. However, reference (Okedu et al., 2020) proposed the potential of small hydropower in contributing as one of the off-grid options in the country. These options are often unable to cater for consumers' needs adequately because the capital cost and the technicalities involve in the technology represents a big share of the project and its feasibility (Nfah, 2013). This could be ascertained as reported in reference (Kaundinya et al., 2009), where a comparative analysis was done for grid connected and standalone options.

The generation capacity and grid transmission infrastructures in Nigeria are inadequate and unsustainable to attain the sustainable development goal of 2030 deadline. One of the ways to address this issue is by the use of biomass energy system. Among all the renewable energy resources, biomass can be stored and utilized on-demand, contrary to discontinuous solar and wind energy resources (Balestrino et al., 2007). Rice husk, one of the most available biomass sources is the largest contributor to the total renewable energy use in Nigeria. The quantity of rice by-products generated in Nigeria is about 1 Mt/y (Ubwa et al., 2014). One of the primary applications of rice husk is heat and power generation. There is an increasing interest to utilize rice husk instead of conventional fossil fuel, as a clean, inexpensive, and secure domestic energy source, especially where fossil fuel is not available. It also enhances energy security and creates jobs for sustainable development and economic growth.

Numerous researches have been done on rice husk to electricity generation in the literature. In order to provide evidence of the knowledge gap that justified the need of this work and support the methodology that was employed in this paper, related literatures were reviewed. The literatures reviewed were used to show the limitations of existing studies by focusing mainly on studies that relied on rice husk to electricity generation. The literature review was also used as a source of information for comparison and referencing in this study. However, the focus was on a selected set for the purpose of this paper. In the literature, two gasification techniques namely: Biomass Integrated Gasification Combined Cycle-atmospheric (BIG/CCa) and the Biomass Integrated Gasification Combined Cycle-pressurized (BIG/CCp), were reported based on a study of the potential for electricity generation from rice husk in Vietnam. The potential for electricity for BIG/CCa was 278 MW while that of BIG/CCp was 2,618 MW. Although the study considered the potential of electricity generation from rice husk, it did not consider load assessment, levelized cost of electricity and the design of the gasifier. Similarly work was carried out in reference (Gabbar et al., 2017). Pode, Diouf and Pode (Pode et al., 2015), examined sustainable rural electrification using rice husk biomass energy; Cambodia was used as a case study. Gasification technology was used for the power generation. The availability of rice husk in the country was estimated to be 1.6 Mt/y with 10 MW installed power capacity. The work considered generation of power using rice husk gasification technology only. They system's levelized cost of electricity, the design of the gasifier and load assessment were not considered. Song, Paul, Lin and Juch (Song et al., 1998), used the laboratory-scale fixed-bed and bench-scale downdraft approaches to gasify rice husk at 760–900 K to generate electricity. From their findings, 10 kW of electricity was generated by gasifying approximately 28 kg/h of rice husk. But they did not consider the potential of electricity generation from rice husk, gasifier design, levelized cost of electricity and load assessment. Ahiduzzaman and Islam (2009), reported gasification procedure for power generation using rick husk feedstock. Their gasifier was designed throat less in order to maintain uniform pressure in the thermochemical reactor. However, the potential of electricity generation from rice husk, the minimum selling price of electricity and energy auditing of the location were not considered. Asanka and Perera (2014) assessed the potential and viability of rice husk based power generation in Sri Lanka. Their work investigated the possibility of using rice husk as a viable source of power generation in Sri Lanka. The total rice husk production of was about 800 kt/y. This rice husk can potentially generate 180 GWh/y of electricity. The designs of the gasifier, minimum selling price of electricity and energy auditing of the study area were not considered. Kini, Chandrashekara and Radhakrishna, (Kini et al., 2016), used a case study of mills in India to study power generation from rice husk. Gasification technique and the produced electrical power were used to test a 100 kW rice mill situated at a village Soraba, in Karnataka state, India. Although the work considered only the likelihood of electricity generation from rice husk, gasifier design and levelised cost of electricity was not considered. Most of these studies centred on potential of electricity generation using rice husk and do not take into account the levelized cost of the power they generate. The detailed design and analysis of the gasification system for secondary filtration of the producer gas was not done.

In light of the above literature on rice husk to electricity conversion using gasification technology, one possible way to evaluate the rice husk fired plant is to compare the same system with conventional fossil fuel. In this study, an off-grid electricity generation in Nigeria based on rice husk gasification technology was developed to evaluate the potential of electricity generation, the life cycle energy use and the cost of producing electricity from rice husk. The specific objectives of this study are (i) to conduct energy auditing of the study area in order to determine its total energy consumption; (ii) to conduct resource assessment (rice husk availability) of the study area in order to know if the available rice husk can cater for its total energy consumption; (iii) to develop an empirical model to quantify gasifier electric power output; (iv) to design the gasifier system using system mass and energy balance; and (v) to perform techno-economic assessment to estimate the energy use and minimum selling price (tariff) of electricity production and compare these with national power grid. These issues are considered in the present study, thereby bridging the knowledge gap.

2. Methodology

Mass and energy balance were used to design the gasifier system; AUTODESK INVENTOR PROFESSIONAL 2015 (AUTODESK KNOWLEDGE NETWORK, 2015) was used to produce the design; while the levelized cost of electricity was used to access the economic viability of the system. Also, the detailed gasifier system design was done. Fig. 1 shows the block diagram of the gasification system for electricity generation, using rice husk as input. The selected location for this study is Adani, in Uzo-Uwani Local Government Area (LGA) of Enugu state, eastern Nigeria. Adani is bound to the north by Nsukka LGA, to the east by Udi LGA, and to the south by Ayamelum LGA in Anambra state. The nearest urban centre is Nsukka, which is about 15–20 km away from Adani.

2.1. Estimation of energy demand for adani

For ease of analysis, the electricity demand was grouped into four categories: domestic purposes, industrial/commercial purposes, school/religion purposes and health purpose. The total electrical load of Adani was estimated to be 850.054 kW; with total daily, month and yearly energy demands of 8,991 kWh, 269.7 MWh and 3,236.8 MWh. The load assessment was done in excel worksheet, using customized data templates for this purpose.

2.2. Resource assessment

The purpose of the resource assessment is to know if the availability of rice husk in the study area has power potential to cater for the total load of the area. The availability of rice husk in Adani was assessed using the 36 rice mills in the location. The rice mills were named M1, M2, M3, - M36. The daily production of rice husk in each rice mill was gathered and measured in per week basis (every Saturday) in each rice mill using a weighing balance. The measurement was done for a period of 12 months (from November 2018 to October 2019). From the assessment done, the annual availability of rice husk in Adani is 3,636 t/y.

2.3. Mathematical modelling of rice husk power plant

In this study, the annual output energy of the system, E_{out}, is a function of the output power (P_{out}) and the Capacity Utilization Factor (CUF) and was calculated using,

$$E_{out} = P_{out} \times 8,760 \tag{1}$$

Putting the CUF of the plant into consideration, the annual energy output is:

$$E_{out} = P_{out} \times 8,760 \times CUF \tag{2}$$

Where:

E_{out} is the annual output energy of the system in Wh or kWh or MWh or GWh.
P_{out} is the rated power of the system in Wh or kWh or MWh or GWh.
CUF is the Capacity Utilization Factor.

The power rating of the rice husk gasifier was calculated using,

$$P_{out} = \frac{M_{rh} \times 1,000 \times CV_{rh} \times \eta_g}{365 \times 3,600 \times t_g} \tag{3}$$

Where:

M_{rh} is the annual availability of rice husk in the study area.
η_g is the conversion efficiency of the gasifier system.
t_g is the operating hour of the gasifier system in a day.
CV_{rh} is the calorific value of the rice husk.

The potential power capacity of Adani was calculated using equation (4);

$$S_{bg} = \frac{P_{bg}}{Cos\theta} \tag{4}$$

Where:

S_{bg} is the potential power capacity of the rice husk gasifier system in MVA,
P_{bg} is the potential real power of the rice husk gasifier system in MW
$Cos\theta$ is the power factor of the generator, 0.8 was assumed for power factor in this design.

2.4. Rice husk power gasification design

The potential power capacity of Adani using the available rice husk is $S_{bg} = 2\,MVA$. This capacity was split into four units, that is; $S_{bg} = 4 \times 500\,kVA$ in order to achieve power supply reliability and optimal operation. One of the 500 kVA gasifier plants was designed, and it was duplicated into four units. Fig. 1 shows the block diagram of the design. Before the components design was done, the rice husk chemical mass and energy balance of the system was done; this helped to quantify the

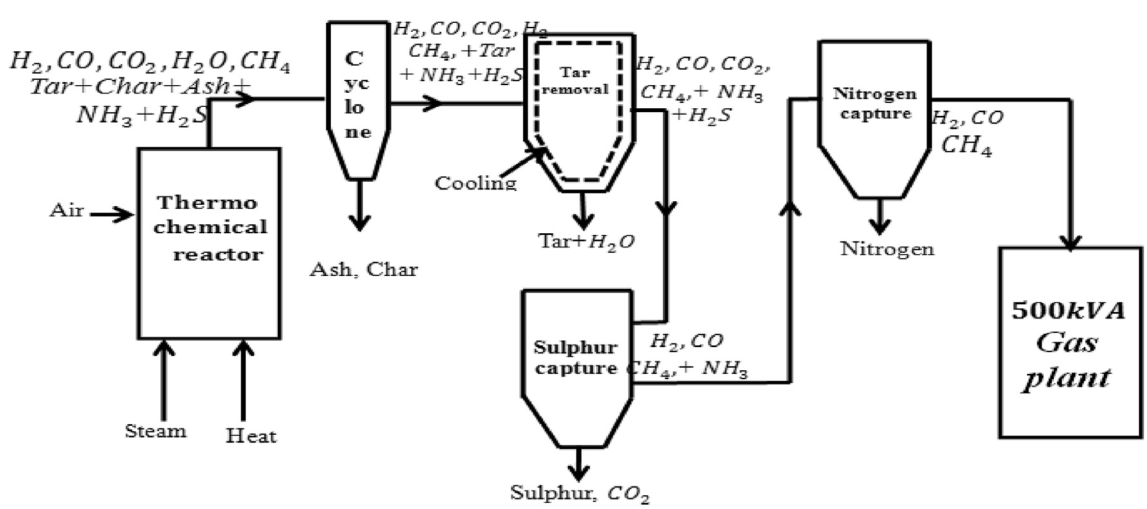

Fig. 1. Gasification system for electricity generation.

components design.

2.4.1. The system mass balance

The mass balance in this design has three purposes which are to;

i. Determine the volume of producer gas in a given quantity of rice;
ii. Get the amount of air required to completely oxidize the given quantity of rice husk;
ii. Know the amount of steam required to completely decompose the given quantity of rice husk.

Basically, rice husk contains: 51.2% carbon, 5% hydrogen, 36% oxygen and 0.7% nitrogen; while producer gas contain: 21% carbon monoxide, 10% carbon dioxide, 2.5% methane, 52% nitrogen, 1% water vapour and 13.5% hydrogen gas. This information was use to do the mass balance. To calculate the volume of producer gas, carbon balance of the system was done.

In this system mass balance, 1 kg of rice husk was taken as the basis.

Let the producer gas in the system be Y kg-mole.

Then,

$$C\ in\ rice\ husk = C\ in\ producer\ gas + C\ in\ ash + C\ in\ tar \tag{5}$$

Where C is carbon.

Doing the carbon balance of the system, carbon input is equal to carbon output, then:

$$C\ in\ producer\ gas = (C\ in\ CO_2 + C\ in\ CO + C\ in\ CH_4)Y + C\ in\ ash + C\ in\ tar \tag{6}$$

$$0.043 = (0.1 + 0.21 + 0.025)Y + 0.029 = 0.335Y + 0.029$$

$$Y = 0.042\ kg - mole$$

Therefore, the producer gas in 1 kg of rice husk is $Y\ =\ 0.042\ kg - mole$.

Applying gas law, noting the Standard Temperature and Pressure (STP) conditions, the volume of the producer gas in 1 kg of rice husk is $1.056\ m^3$

Removing the percentage impurities – nitrogen, water vapour and carbon dioxide (63%) from the producer gas, yields:

$$V_p = 1.056 - \left(\frac{1.056 \times 63}{100}\right) = 0.3907\ m^3$$

Then, $V_p = 0.3907\ m^3$; this implies that the volume of the pure producer gas in 1 kg of rice husk is $V_p\ = 0.3907\ m^3$.

The next task is to determine the amount of air that will completely oxidize 1 kg of rice husk using moist air as source of the oxidant with relative humidity of 80%, at atmospheric pressure of 740 mmHg, considering partial pressure of steam as $P_s^{H_2O}\ =\ 26\ mmHg\ at\ 25\ ^\circ C$.

Nitrogen balance was done to get the amount of air required.

$$N_2\ in\ rice\ husk + N_2\ in\ moist\ air = N_2\ in\ producer\ gas \tag{7}$$

Substituting into equation (7), yields:

$$0.00025 + 0.7677X = 0.022 \equiv 0.7677X = 0.02175 \tag{8}$$

From equation (8),

$$X = 0.028\ kg - mole$$

Applying gas law and noting STP condition, the volume of air required to oxidize 1 kg of rice husk is $0.712\ m^3$.

To determine the amount of steam that is required to decompose 1 kg of rice husk, hydrogen balance of the system was done. Let Z kg-mole be the steam required to decompose 1 kg of rice husk. Doing hydrogen balance gives:

$$H\ in\ RH + H\ in\ moist\ RH + H\ from\ steam + H\ in\ moist\ air = H\ in\ producer\ gas \tag{9}$$

Where H is hydrogen and RH is rice husk.

Therefore,

$$0.025 + 0.0017 + Z + 0.00084 = (0.025 + 0.135 + 0.01) \times 0.044)$$

$$0.02754 + Z = 0.00748$$

$$Z = 0.02\ kg - mole$$

Applying gas law and noting STP condition, the volume of air required to oxidize 1 kg of rice husk is $0.504\ m^3$.

2.4.2. The system energy balance

The aim of energy balance is to determine the amount of energy required for the rice husk gasification. The energy can be introduced as work (W) or heat (Q), that is:

Let the amount of energy required for the rice husk gasification be E_{in}.

$$E_{in} = E_{RH} + E_a + E_s \tag{10}$$

Where:

E_{RH} is amount of energy required to completely oxidize a fixed volume of rice husk
E_a is the enthalpy of moist air
E_s is the enthalpy of steam

Using Dulong's formula for biomass,

$$E_{RH} = G_{CV} - Heat\ of\ vaporation\ of\ water \tag{11}$$

But:

$$G_{CV} = 81\ \%\ carbon + 341\left(\%\ Hydrogen - \%\ \left(\frac{Oxygen}{8}\right)\right) \tag{12}$$

$$Heat\ of\ vaporation\ of\ water = 5.84\ (9\ \%\ H + 1.7\ \%\ of\ water\ in\ rice\ husk) \tag{13}$$

The enthalpy of moist air was calculated as:

$$E_a = h_a + Xh_w \tag{14}$$

Where.

h_a is the specific enthalpy of dry air.
h_w is the specific enthalpy of water vapour.
X is mass of water vapour

$$h_a = C_{pa} \times T \tag{15}$$

C_{pa} is the heat capacity of air and T is the operational temperature.

$$h_w = C_{pw}T + h_{we} \tag{16}$$

C_{pw} is the heat capacity of water and h_{we} is evaporation heat of water.

Substituting into equation (14), gives:

$$E_a = \left[C_{pa} \times T\right] + X\left[C_{pw}T + h_{we}\right] \tag{17a}$$

The enthalpy of steam was calculated as:

$$E_s = E_{25\ ^\circ C-100\ ^\circ C} + E_{100\ ^\circ C-100\ ^\circ C} + E_{100\ ^\circ C-700\ ^\circ C} \tag{17b}$$

Where.

$E_{25\,^{\circ}C-100\,^{\circ}C}$ is the heat required to raise temperature from 25 °C to 100 °C
$E_{100\,^{\circ}C-100\,^{\circ}C}$ is the heat required to convert water at 100 °C to 100 °C steam
$E_{100^{\circ}C-700^{\circ}C}$ is the heat required to convert 100 °C steam to 700 °C.

The energy balance was done at constant volume and the pressure was obtained using:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} = \frac{P_3}{T_3}\ etc \tag{18}$$

2.4.3. Gasifier thermochemical reactor design

Here, the following was determined:

i. The height of the oxidation and reduction (redox) zone of the reactor;
ii. Reactor diameter;
ii. Height of the reactor.

2.4.3.1. Height and diameter of the reactor's oxidation and reduction zone.

From JMP Limited 500 kVA gas generator datasheet, the generator consumes 118 m^3/h of gas at full load,

$$\text{the amount of RH required by the generator at full load is } \frac{118}{0.3907} = 302.02\,kg\Big/h.$$

$$Volume\ of\ oxidation - reduction\ (redox)\ zone = \frac{302}{128} = 2.3577\ m^3$$

But,

$$Volume\ of\ the\ redox\ zone = \pi r^2 h = 2.3577\ m^3 \tag{19}$$

Where:

r is the radus of the reactor in m
h is the height of the redox zone in m.

Obtaining the diameter of the reactor helped in getting the radius of the reactor from where the height of the redox zone was evaluated. The diameter of the reactor was calculated using:

$$D_r = \left[\frac{1.27 \times FCR}{SGR}\right]^{0.5} \tag{20}$$

Where:

D_r is the reactor diameter in m
FCR is the RH consumption rate in kg/h, substituting into equation (20) gives;

the height of the redox zone was obtained as

$$h = \frac{D_r}{\pi r^2} \tag{21}$$

The area of the redox zone was calculated using: πr^2 (22)

The height of the thermochemical reactor which is referred to the total distance from the top to the bottom end of the reactor was calculated using:

$$H = \frac{SGR \times T}{Average\ bulk\ density\ of\ RH} \tag{23}$$

T is the required time to totally gasify the rice husk inside the reactor.

$$T = \frac{Average\ bulk\ density\ of\ RH\ \times\ V_r}{FCR} \tag{24}$$

2.4.4. Cyclone separator design

In this design, 1D3D cyclone was adopted in order to achieve higher collection efficiency. The "D" is the cyclone barrel diameter. The cyclone has the following properties: the cyclone diameter is D_c; the length of the barrel is $L_c = 1 \times D_c$, the length of the cone is $Z_c = 3 \times D_c$; the diameter of dust outlet is $J_c = \frac{D_c}{4}$; the diameter of the clean gas outlet is $D_e = \frac{D_c}{2}$ and the diameter of the dusty gas inlet is $H_c = \frac{D_c}{2}$.

This 1D3D cyclone has design velocity of 16 $ms^{-1} \pm 2\ ms^{-1}$. The task is to determine the dimensions of the cyclone parts.

2.4.4.1. Determination of dimensions of the cyclone parts.

The cyclone design velocity and the system gas flow rate are the basis to size a cyclone. The diameter of the cyclone was obtained using equation (25).

$$D_c = \sqrt{\frac{8Q}{V_i}} \tag{25}$$

Where:

Q is the gas flow rate in m^3/s and V_i is the inflow gas velocity in ms^{-1}.

$$Q = V_i \times A \tag{26}$$

Where A is the area of the gas outlet of the thermochemical reactor in m^2.

$$A = \frac{\pi d^2}{4} \tag{27}$$

2.4.5. Gas scrubbers design

Venturi scrubber with 3D0.5D cyclone separator was adopted because of its high gas collection and cleaning efficiencies. The throat velocity and cross-sectional area was estimated using a modified Bernoulli equation as shown in equation (28):

$$V_t = \frac{Q_m}{A_t} \tag{28}$$

Where:

V_t is the scrubber throat velocity in ms^{-1};
A_m is the scrubber throat cross-sectional area in m;
Q_m is the gas flow rate in m^3/s.

The property of this scrubber is as follows:

The scrubber cyclone diameter is D_s; the length of the barrel is $L_s = 3 \times D_s$; the length of the cone is $Z_s = 0.5 \times D_s$; the diameter of dust outlet is $J_s = \frac{D_s}{4}$; the diameter of the clean gas outlet is $D_{es} = \frac{D_s}{2}$ and the diameter of the dusty gas inlet is. $H_s = \frac{D_s}{2}$.

The throat cross-sectional area was calculated from the scrubber inlet and throat velocities as shown in equation (29):

$$A_t = A_i \times \frac{V_t}{V_i} \tag{29}$$

A_t *and* A_i are areas of the throat and inlet of the scrubber respectively.

The inlet cross-sectional area was calculated using;

$$A_i = \frac{\pi d^2}{4} \tag{30}$$

From the scrubber cross-sectional area, the dimensions of the throat of the scrubber was estimated. The diameter of the throat was found using equation (31).

$$d_t = \sqrt{\frac{4 \times A_t}{\pi}} \quad (31)$$

The length of the scrubber throat is related to its diameter as:

$$l_t = 3 \times d_t \quad (32)$$

The length of the diverging section of the scrubber throat is related to its diameter as:

$$l_{div} = 4 \times d_t \quad (33)$$

The diameter of the cyclone part of the scrubber was estimated using equation (34).

$$D_s = \sqrt{\frac{16Q}{V_i}} \quad (34)$$

2.4.6. *Gas storage design*

In this design, simple cyclone gas storage design was adopted. 3D0.5D cyclone was adopted for this gas storage, and the properties are:

The gas storage cyclone diameter is D_s; the length of the barrel is $L_s = 3 \times D_s$; the length of the cone is $Z_s = 0.5 \times D_s$; the diameter of the clean gas outlet is $D_{es} = \frac{D_s}{2}$; and the diameter of the pure gas inlet is. $H_s = \frac{D_s}{2}$.

The gas storage parameters were obtained following the same way as that of the gas scrubber design. The process flow diagram of the designed gasifier system is as shown in Fig. 2, while its corresponding stream table is as shown in Table 1.

2.5. *Techno-economic analysis of the rice husk gasifier power plant*

The techno-economic analysis of the power plant was done in order to determine the minimum selling price (levelized cost) of electricity of the power plant. The Annualized Cost of the total System (ACS) is as shown in equation (35):

$$ACS = 4C_{acs} \quad (35)$$

Where:

C_{acs} is the annualized cost of the total system and the constant, 4, shows the numbers of 500 kVA generation systems capacity of the study area.

C_{acs} was further explained in detail which possesses all kinds of costs as shown in equation (36):

$$C_{acs} = C_{acc} + C_{arc} + C_{amc} + C_{afc} - C_{sc} \quad (36)$$

Where:

C_{acc} is the annualized capital cost,
C_{arc} is the annualized replacement cost,
C_{amc} is the annualized maintenance cost,
C_{afc} is the annualized fuel cost,
C_{sc} is the salvage value of the designed biopower system.

2.5.1. *Annualized capital cost (C_{acc})*

In this work, the capital cost of the power plant includes the cost of fabricating, installing and purchasing of components for the rice husk power system. The annualized capital cost was calculated by using Capacity Recovery Factor (CRF). In this paper, C_{acc} was calculated as,

$$C_{acc} = C_{cc} \times CRF \quad (37)$$

Where:

C_{cc}, is the capital cost of the system,
*CRF*is the capital recovery factor of the system for a lifetime of n years and discount rate r, CRF was calculated as,

$$CRF(r,n) = \frac{r(1+r)^n}{(1+r)^{n-1}} \quad (38)$$

In this study, the lifetime of the project was calculated by employing:

$$\mathrm{n} = \frac{N_{gl}}{N_{go}} \quad (39)$$

Where:

N_{gl} is the generator lifetime (in hours) and N_{go} is the generator operation hours during one year.

Substituting into equation (39), gives:

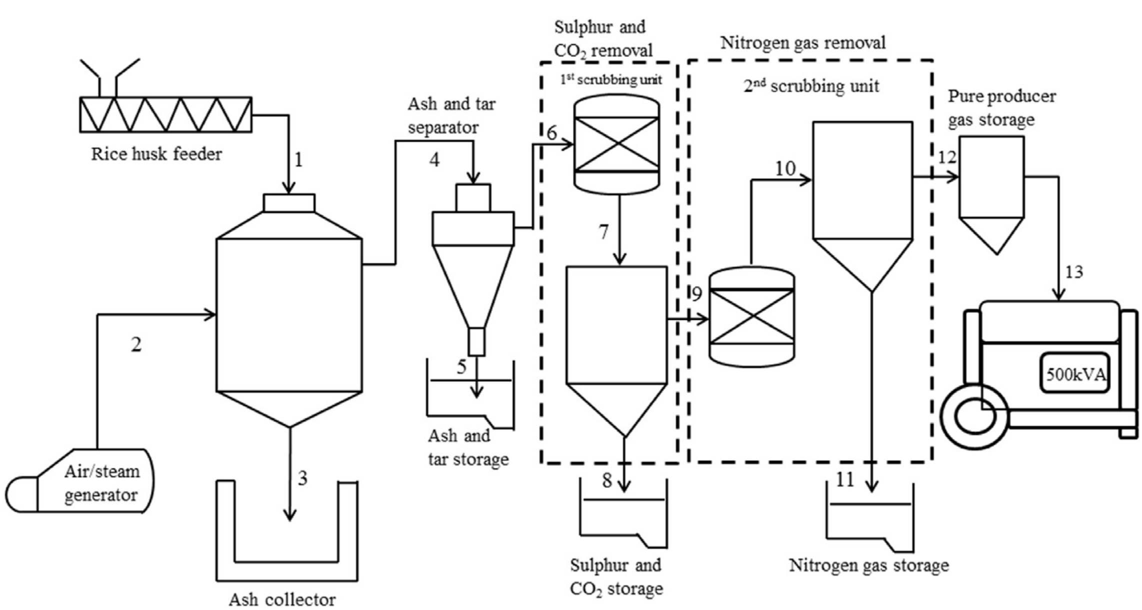

Fig. 2. The process flow diagram of the gasifier system.

$$n = \frac{25 \times 365 \times 24}{20 \times 365} = 30\ y$$

In this work, 10% discount rate on the capital cost was offered; substituting into equation (38), results to:

$$CRF = \frac{0.1(1+0.1)^{30}}{(1+0.1)^{29}} = 0.110$$

From the cost template as shown in Appendix 1, the capital cost of the system is ₦ 84, 919,520.

Substituting into equation (37) gives the annualized capital cost as:

$$C_{acc} = 84,919,520 \times 0.110 = 9,341,147\ Naira$$

2.5.2. Annualized replacement cost (C_{arc})

The C_{arc} of this work is the cost of replacing the components of this project at the end of life time of the bio power system. The C_{arc}, which occurred during the lifespan of the project was calculated using;

$$C_{arc} = C_{rc} \times CRF \times \frac{1}{(1+r)^y} \tag{40}$$

Where:

C_{rc} is the replacement cost of the components
y is the lifetime of the biomass gasifier system in years. The replacements are essential if the lifetime of the project is more than component lifetime.

From the cost template as shown in Appendix 1, the replacement cost of the system for the total life cycle is ₦ 1,500,000. Substituting into equation (40) gives the annualized replacement cost as:

$$C_{arc} = 1,500,000 \times 0.110 \times \frac{1}{(1+0.1)^{30}} = 9,456\ Naira$$

2.5.3. Annualized maintenance cost (C_{amc})

In techno-economic analysis, project maintenance cost is the cost of ensuring that the project components are functioning very well as well as the cost of component repair. The maintenance cost per hours of the bio power system include; labour costs, repairing and other charges to operate the system and it was calculated using this expression:

$$C_{amc} = N_{rh} \times C_{hm} \tag{41}$$

In equation (41), N_{rh} is the hour of running of biomass gasifier and C_{hm} is the hourly maintenance cost of the gasifier system. From the cost template as shown in Appendix 1, the hourly maintenance cost of the system is ₦180. Substituting into equation (41) gives the annualized capital cost as:

$$C_{amc} = 180 \times 20 \times 365 = 1,314,000\ Naira.$$

2.5.4. Annualized fuel cost (C_{afc})

The input feedstock used as a fuel in this work is rice husk. In this study, the fuel cost is equal to the amount of rice husk feedstock consumed over a year (in kg) multiplied by the price of rice husk (₦/kg). The C_{afc} was calculated using this formula:

$$C_{afc} = C_{rh} \times E_{bp} \times q(t) \tag{42}$$

Where.

C_{rh} is the price of rice husk feedstock in per kg,
E_{bp} is the total energy generated by the bio power system in (kWh/y),
$q(t)$ is the rate of rice husk consumed (kg/kWh) by the bio power system.

From the cost template as shown in Appendix 1, the price of rice husk per kilogram is ₦5. Substituting into equation (42) gives the annualized capital cost as:

$$C_{afc} = 13,132,800kWh \times 5 \times \frac{302}{4,000} = 4,957,632\ Naira$$

2.5.5. Salvage value (C_{sc})

Salvage value is the value remaining of a component at the end of project life. The salvage value of this project was calculated using this formula:

$$C_{sc} = C_{arc} \times \frac{R_{rl}}{N_{ls}} \tag{43}$$

Where.

C_{arc} is the replacement cost of the component,
R_{rl} is the remaining life of the project system
N_{ls} is the life span of the gasifier system.

The remaining life of the bio power was obtained from scrab value of the project. Stainless steel lasts for more than 40 years. Also, the generators can be sold as scrab. So, the remaining life of the gasifier is 10 years. Substituting into equation (43) yields:

$$C_{sc} = (1,500,000 + 9,020,000) \times \frac{10}{30} = 3,506,667\ Naira.$$

Substituting into equation (35) gives:

$$C_{acs} = 9,341,147 + 9,456 + 1,314,000 + 4,957,632 - 3,506,667 = 12,115,568\ Naira.$$

Therefore, the annualized cost for the rice husk power plant is: $12,115,568$ *naira*

Substituting into equation (36) to get the Annualized Cost of the total System, (ACS) gives:

$$(ACS) = 4 \times C_{acs} = 4 \times 12,115,568\ Naira = 48,462,272\ Naira\,/\,y$$

The key economic factor which defines cost effectiveness of this rice husk power system is levelised cost of electricity. The levelised cost of electricity is defined as the ratio of the annualized system cost to the kWh of the effective electricity produced by the system and it was calculated using:

$$LCOE = \frac{ACS(Naira/y)}{Total\ electrical\ load\ served\ (KWh/y)} \tag{44}$$

From the design, the total yearly kilo watt-hour of the study area is 13, 132, 800 kWh/y.

Substituting into equation (44), we obtain:

$$LCOE = \frac{48,462,272}{13,132,800} = 3.69\ Naira \Big/ kWh$$

3. Results and discussion

This section presents the results of this research work. The results of the electrical load and energy demands of the study area were presented, before the resource assessment results. The outcomes of the detailed design of the rice husk gasification system were presented and the economic viability of the designed system was also considered.

3.1. Electrical load and energy demand results

During the onsite study, the electrical load of Adani was grouped into four categories: household purpose electrical load, industrial/

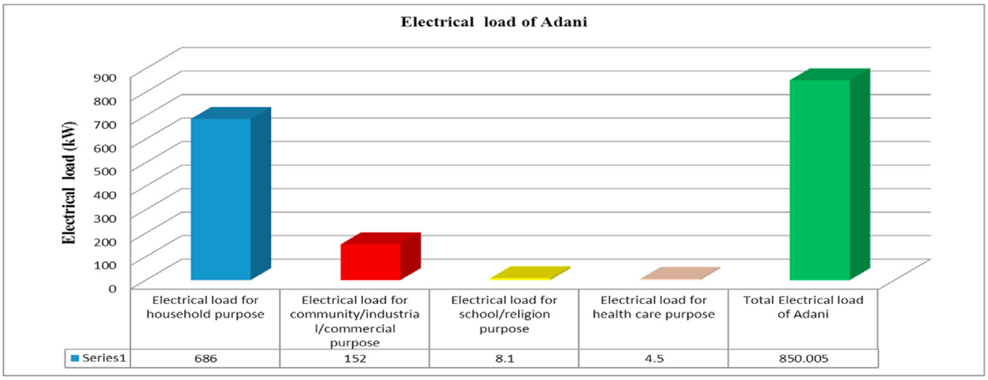

Fig. 3. Electrical load of Adani.

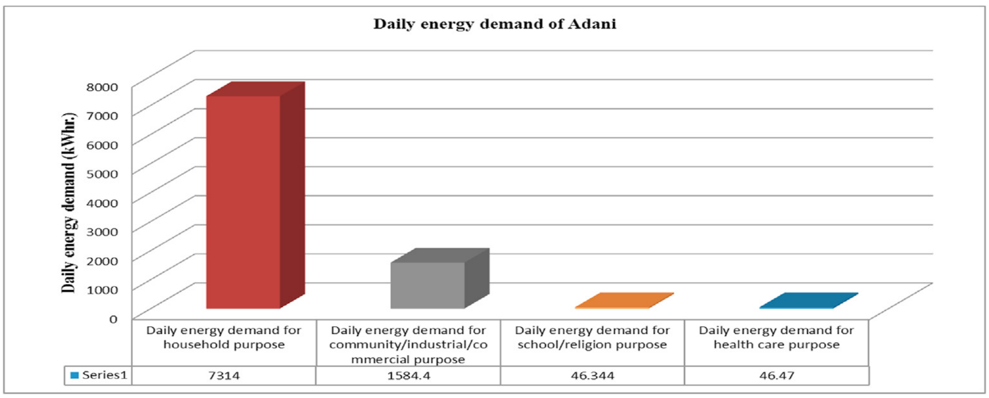

Fig. 4. Daily energy demand of Adani.

commercial purpose load, school/religion purpose load and health care purpose load. As shown in Fig. 3, the household purpose load is 686 kW, industrial/commercial purpose load is 152 kW, school/religion purpose load is 8.1 kW and health care purpose load is 4.5 kW. The total electrical load of Adani is the summation of the individual purpose loads, which is 850.005 kW. Fig. 4 shows the daily energy demand of each of the categories of the load demand. The daily energy demand of household purpose, industrial/commercial purpose, school/religion purpose and health care purpose are: 7,314 kWh, 1,584.4 kWh, 46.344 kWh and 46.46 kWh.

The total daily, monthly and yearly energy demand of Adani as shown in Fig. 5 are: 8,991 kWh, 269,736.42 kWh and 3,236,837.04 kWh.

3.2. Resource assessment/power potential results

Fig. 6 shows the availability of rice husk in kg in Adani from November 2018 to October 2019. As seen in Fig. 6, the availability of rice husk in kilogram from November 2018 to October 2019 are: 399,060 kg, 674,250 kg, 217,650 kg, 164,600 kg, 108,250 kg, 294,450 kg, 212,000 kg, 180,000 kg, 196,000 kg, 300,000 kg, 420,000 kg and 510,000 kg respectively. Summation of all the monthly availability of rice husk gave the annual availability of 3,636,000 kg rice husk. Using rice husk gasification power model, this annual availability of rice husk has the potential of 1,520,534.247 W of electricity generation. This potential of

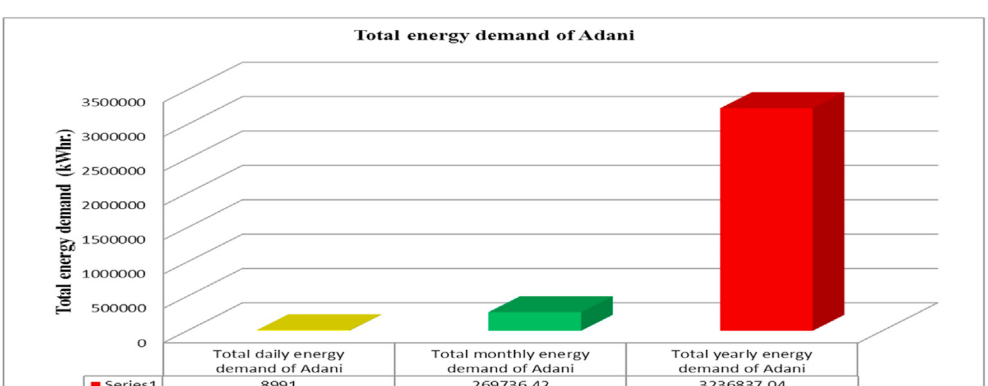

Fig. 5. Total energy demand of Adani.

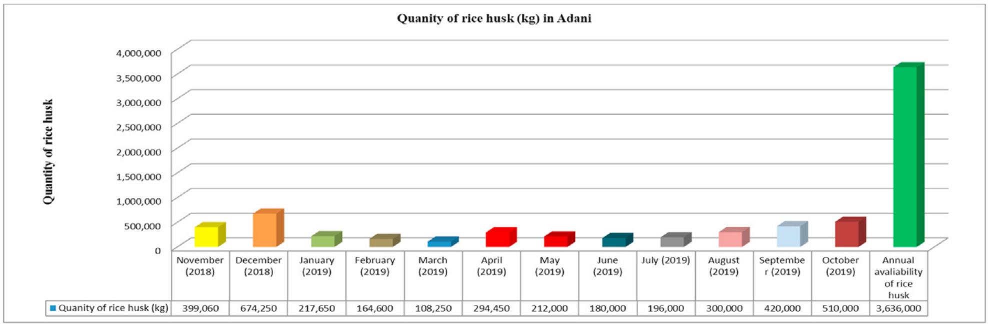

Fig. 6. Availability of rice husk in Adani.

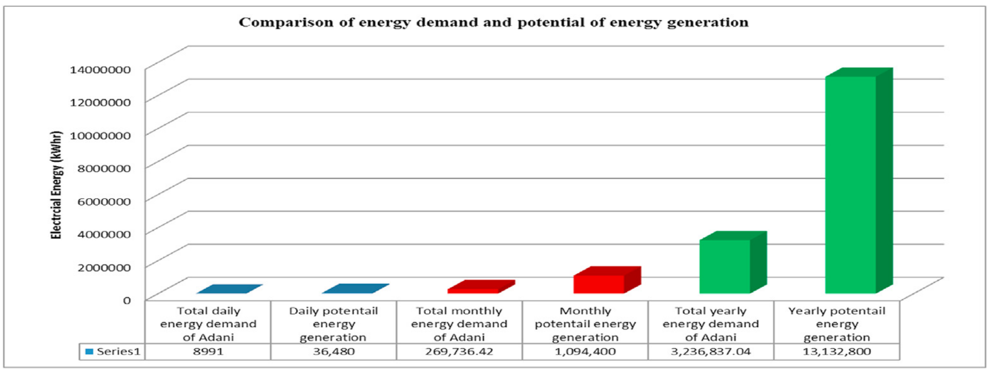

Fig. 7. Estimated energy demand and potential energy generation.

electricity generation has power station capacity of 1.9 MVA which is approximately equal to 2 MVA.

Fig. 7 shows the comparison of estimated energy demand of Adani to the potential of electricity generation using rice husk in Adani. The estimated total daily, monthly and yearly energy demands of Adani are: 8,991 kWh, 269,736.42 kWh and 3,236,837.04 kWh. While the total potential daily, monthly and yearly energy generation there are: 36.48 MWh, 1,094.4 MWh and 13,132.8 MWh.

It is obvious from Fig. 6, that the potential daily, monthly and yearly energy generation is higher than estimated total daily, monthly and yearly energy demands.

3.3. Rice husk gasification design

3.3.1. Thermochemical reactor (gasifier) design

Gasification of the rice husk takes place in the thermochemical reactor to generate producer gas. The producer gas of rice husk gasification mostly comprises of H_2, CO, CO_2, CH_4 (which can be used for power generation, liquid fuel synthesis, production of pure hydrogen or production of chemicals) and contaminants. The contaminants are highly undesirable for the downstream processes because of their severe impacts on the equipment, downstream catalysts, and environment. Tars, N-containing compounds (mainly NH_3) and S-containing compounds (mainly H_2S) are the notorious ones among all of the contaminants in the producer gas from rice husk gasification for downstream applications.

The contaminants in the producer gas can dramatically foul and clog the equipment in the system, which significantly increases the cost of repairing and maintenance. Moreover, they can also inactivate or poison the catalysts used in downstream processes and pollute the environment. Therefore, these impurities must be destructed or removed stringently to meet the acceptable levels, which depends on the downstream applications. The efficiency of these impurities removal depends on the type of gasifier technology, operating temperature, type of biomass feedstock and steam/biomass ratio. Among these affecting factors, gasification temperature and gasification type are the most important parameters significantly influencing the composition of contaminants in the producer gas. It has been proven, both theoretically and experimentally, that the producer gas generated from downdraft gasifiers at high gasification temperature with rice husk as biomass feedstock has less tars than that from fluidised bed gasifiers, and much less than that from updraft gasifiers. This is because in the updraft gasification, when the up-flowing hot gasification agent (air/oxygen/steam) contacts the downward moving biomass at the gasifier bottom, the biomass is pyrolysed and then gasified at the operation temperature. While the producer gas moves upwards, it heats up the biomass and the biomass is then decomposed into volatiles and tars which are carried up by the producer gas for downstream application. In this work, downdraft gasifiers at operating temperature of 700 °C and above were considered. This was used to achieve primary filtration of the producer gas.

From 500 kVA Caterpillar gas generator datasheet obtained from JMP Limited Company, the generator consumes 118 m^3/h of gas at full load. This information was used as the basis of the design. From the system mass balance, 1 kg of rice husk contains 0.3907 m^3 volume of pure producer gas. The quantity of rice husk to produce 118 m^3/h volume of pure producer gas (hydrogen, carbon monoxide and methane) at full load is: 302.02 kg/h. The input energy required to generate this producer gas is $4,014.92$ $kcal$. This information was used to calculate the dimensions of the thermochemical reactor. The height of the redox zone of the thermochemical reactor is 1.2527 m, while the thermochemical reactor diameter is 1.548 m. The area of the redox zone is 1.88 m^2, the volume of the redox zone is 2.3577 m^3 and the height of the thermochemical reactor is 5.296 m.

3.3.2. Cyclone design

The secondary producer gas filtration starts from the cyclone. Gasification of rice husk using downdraft gasifiers at operating temperature 700 °C and above generates insignificant amount of tar and excess of amount of ash. The ash can further be processed and retailed or used in the farms as fertilizer. This shows that our system is environmental friendly as tar which is a major contaminant is extremely low in the producer gas. The producer gas and impurities obtained from the gasification process are passed to the cyclone where some of the impurities like ashes are separated from the producer gas. In this design, 1D3D cyclone design connected in parallel in order to achieve higher collection efficiency was used. The Ds designation refers to the barrel diameter of the cyclone. From the design, the cyclone diameter is 0.25 m ; the length of the barrel is 0.25 m; the length of the cone is 0.75 m; the diameter of dust outlet is 0.0625 m; the diameter of the clean gas outlet is 0.125 m and the diameter of the dusty gas inlet is 0.125 m. To achieve high cyclone separation efficiency, the whole cyclone system was broken down into two smaller identical cyclones connected in parallel arrangement. This is to achieve increased gas velocity and centrifugal force of the cyclone, thus; increasing the separation efficiency. This strategy gave rise to two identical cyclones with the following dimensions: the cyclone diameter is 0.125 m ; the length of the barrel is 0.125 m; the length of the cone is 0.375 m; the diameter of dust outlet is 0.03125 m; the diameter of the clean gas outlet is 0.0625 m and the diameter of the dusty gas inlet is 0.0625 m.

3.3.3. Gas scrubber design

In order to achieve cleaner gas and clean environment, the producer gas was further purified using gas scrubbers to remove hydrogen sulphide, carbon dioxide and ammonia leaving only pure producer gas. Concentrations of N-containing contaminants and S-containing contaminants in the producer gas are strongly dependent on the nitrogen and sulphur contents in the feedstock, gasifier types and gasification operating conditions. Rice husk contains insignificant amount of sulphur and very low amount (0.7%) of nitrogen. In this work downdraft gasifier with air and steam as the oxidizing agents were used. The gasifier system produced low NH_3 and H_2S due to the decrease H radicals from steam reforming in the atmosphere which reduced the availability to react with N-based and S-based volatile compounds and hydrogenation reactions of nitrogen and sulphur in the rice husk.

The gas scrubber is to purify the producer gas by removing N-containing compounds (mainly NH_3) and S-containing compounds (mainly H_2S) and CO_2 from the producer's gas. The design contains two identical gas scrubbers – one for nitrogen gas removal and the other for gas sweetening (sulphur and CO_2) removal. The removal of nitrogen gas was done through cryogenic distillation. Removal of hydrogen sulphide from contaminated producer gas is called sweetening. The process also removes carbon dioxide. The sweeting process is based on the fact that both hydrogen sulphide and carbon dioxide are weak acids and therefore they can react with weak bases. The sweetening agent used in this work is diethanolamine. The reason why this sweetener was chosen is because it has a mildly basic compound with low vapour pressure. This is to ensure that the producer gas is not contaminated in order to achieve cleaner environment. Another important reason diethanolamine was chosen is that it can be recovered and re-used repeatedly. Thus, it is both effective and economical. Venturi gas scrubber with cyclone separator was adopted because of its high gas collection and cleaning efficiencies. First, the throat of the venturis gas scrubber was designed with the diameter, length and area of the throat being 0.112 m, 0.336 m *and* 0.009875 m^2. The length of the diverging section of the scrubber throat was determined as 0.448 m. The diameter of the cyclone part of the scrubber is 0.502 m. 3D0.5D cyclone was adopted for this scrubber and the following dimensions of the cyclone were obtained: the length of the barrel is 1.506 m; the length of the cone is 0.251 m; the diameter of dust outlet is 0.1255 m; the diameter of the clean gas outlet is 0.251 m and the diameter of the dusty gas inlet is 0.251 m.

3.3.4. Gas storage design

The gas storage is for storing the pure gas used for firing the generator. In the design, simple cyclone gas storage was adopted. The gas inlet cross-sectional area is 0.00395 m^2 and the diameter of the cyclone part of the scrubber is 0.251 m. 3D0.5D cyclone was adopted for this gas storage and the dimensions of the gas storage are: the gas storage cyclone diameter is 0.251 m; the length of the barrel is 0.754 m; the length of the cone is 0.126 m; the diameter of the clean gas outlet is 0.1255 m; and the diameter of the pure gas inlet is 0.1255 m.

4. The rice husk gasifier power system mode of operation

Fig. 8 shows the designed rice husk power system components. The component labelled 1 is the water tank. The tank is to store water used for gas cooling and for forming aqueous solution with the gas sweetener. The component labelled 2 is the 500 kVA generator. The generator is for the power generation (4 X 500 kVA). The component labelled 3 is the purified gas storage cylinder. It is the source of gas input to the generator. The two components labelled 4 are the gas scrubbers. They are used for gas purification. The 6th component is the reactor climbing frame for the sole purpose of climbing the thermochemical reactor in order to refill rice husk feed stock. The 7th component is the steam/air generator for generating the oxidants-air and steam. Thermochemical reactor is the 8th component. That is where the gasification takes place. Fig. 9 shows the solid work of Fig. 8. As shown in Figs. 8 and 9, when the rice feed stock of

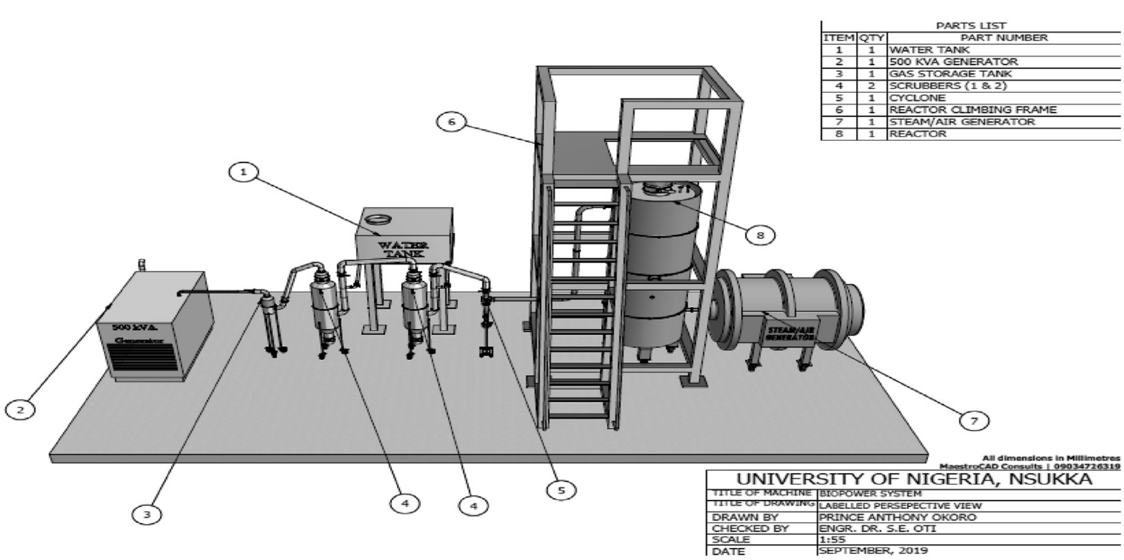

Fig. 8. The rice husk power system components.

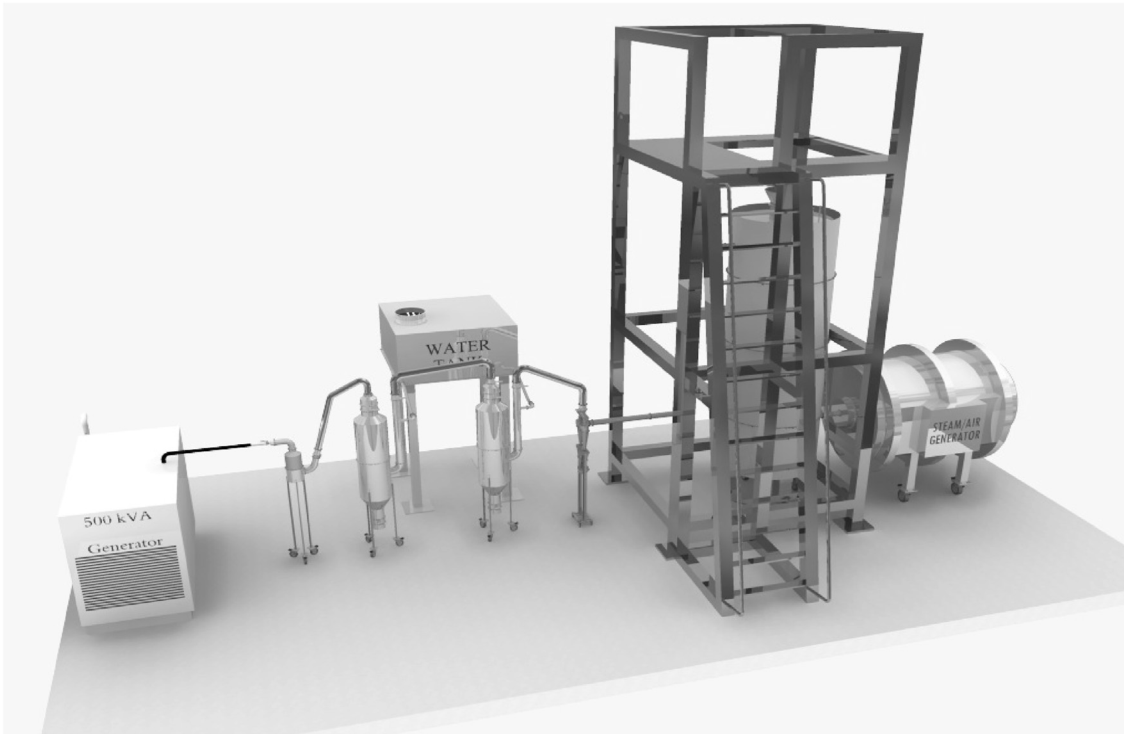

Fig. 9. The solid work of the rice husk power system components.

302 kg is poured into the thermochemical reactor, it occupies the height of the redox zone which is 1.2527 *m*. The area and volume of the thermochemical reactor this 302 kg rice husk occupies are 1.88 m^2 and 2.3577 m^3. 0.1 m above the redox zone is the ignition point of the thermochemical reactor for lighting up the redox zone. Upon igniting the redox zone, the oxidants - air and steam will be introduced to the thermochemical reactor intermediately and temperature within the thermochemical reactor will gradually rise to 700 °C and above. At is time, $H_2, CO, CO_2, H_2O, CH_4,$ *tar, ash,* NH_3 *and* H_2S are produced and pass to the cyclone. The cyclone beats down the tar and ash while H_2, CO, CO_2, H_2O, CH_4, NH_3 and H_2S flows to the first scrubber. This scrubber's function is to sweeten the gas by the removal of CO_2 and H_2S, while H_2, CO, CH_4, and NH_3 flows to the second scrubber where the NH_3 is beaten down from the rest of the producer gases. The pure producer gas, H_2, CO and CH_4, will be stored in the gas storage cylinder which will be used to fire the 500 kVA generator.

4.1. Power dispatch options for the study area

Recall that the capacity of the generation station for the study area is 2 MVA. This capacity was split into 4 X 500 kVA. These four generators are identical. Since they are identical, the incremental full cost will be same. Two options were proposed for the power dispatch to the study area. The first option is loading the generators individually until the total demand of the study area is met. In this option, the house hold electrical load of 686 kW was achieved by loading the first generator to full capacity of 400 kW, which is followed by loading the second generator to 286 kW. The remaining electrical load to commit is the industrial/commercial purpose load, school/religion purpose load and healthcare purpose load, which is altogether 165 kW. This load was committed by loading the second generator to the full capacity, willing its remaining 114 kW power to industrial/commercial purpose load, school/religion purpose load and healthcare purpose load. Doing this, the remaining load to be committed is 165 kW–114 kW = 51 kW. This 51 kW power was supplied by the third generator. The fourth generator acts as a spare/spinning reserve that caters for increment in electrical load demand or a spare generator when one of the committed three generators is undergoing maintenance. The second power dispatch option follows the processing of tieing the total generated power to a bus bar and distributes the power to the individual loads. In the case of the study area, the total electrical load demand is 850.054 kW. The rating of the bus bar for this purpose is 3 kA/415 V. In this option, the three generators that met the electricity demand of the study area were committed and the power they produced was tied to the bus bar from which the power was dispatched to serve the total load of the study area. The fourth generator will be committed accordingly.

4.2. Economics of the rice husk power system

The project lifetime is 30 y with 10% discount rate. The annualized capital cost, annualized replacement cost, annualized maintenance cost, annualized fuel cost and project salvage cost are ₦ 9,020,000, ₦ 9,456, ₦ 1,314,000, ₦ 4,957,632 and ₦ 3,506,667. The LCOE of the designed rice husk power supply option for Adani is 3.6 Naira/kWh, which is cheaper than 30.93 Naira/kWh tariff from national power grid extension to the study area.

5. Conclusion and recommendations for future scope

The rice husk gasification technology for electricity generation presented in this paper is one of the solutions to the global threats associated with increased energy demand such as climate change, environmental pollution, and fossil fuel depletion. It is also one of the ways to solve the issue of Nigeria power challenge, as rice husks are available in high quantity in many locations of the country. This design clearly establishes a technically feasible and economically viable off-grid power solution for rural, commercial and industrial applications, as evident in the case of the study area – Adani. In this paper, an off-grid gasification power supply option for Adani, in Uzo-Uwani Local Government Area of Enugu state, of eastern Nigeria is presented. A detailed load assessment and availability of rice husk for power generation in the study area was conducted. This information was used to design the gasification system with secondary producer gas filtration capacity. The gasification system was designed based on the mass flow rate of producer gas required to power the gas engine at full load. The gasifier was designed downdraft with air and steam as the oxidizing agent, in order to maintain uniform temperature in the oxidation and reduction zones. Furthermore, techno-economic analysis approach was used to determine the economic viability of the designed power system considered in this study. The estimated total load demand of the study area is $850.054\ \text{kW}$. The estimated total daily, monthly and yearly energy demands of the study area are: 8,991 kWh, 269,736.42 kWh and 3,236,837.04 kWh, respectively. The annual availability of rice husk in the study area is $3,636\ \text{t/y}$ and it has potential of $1.52\ \text{MW}$ power generation with daily, monthly and yearly energy generation of: 36.48 MWh, 1,094.4 MWh and 13,132.8 MWh. This potential of electricity generation has power station capacity of 1.9 MVA, which is approximately equal to 2 MVA. This power generation capacity of Adani was used to design each components of the rice husk gasifier. The capacity was divided into four units in order to dispatch the generators economically that is $4 \times 500\ kVA$. One of the 500 kVA gasifier was designed and was duplicated into four units. The Levelized Cost of Electricity of the designed power system is 3.6 Naira/kWh, which is cheaper than 30.93 Naira/kWh tariff from national power grid extension to the study area. Based on the proposed rice husk gasification system, a community could generate power to meet their electricity demand in most economical way, thereby reducing emission, waste and saving cost translating to sustainable development. In light of the above, as part of future research, an off grid power supply option that can serve the whole of Uzo-uwani LGA would be considered. This would act as a hybrid power supply option for more reliable and sustainable generation of electricity in the region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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Appendix 1

Table 1
Capital cost of the gasifier system.

S/N	Items	Quantity	Unit price (₦)	Price (₦)
1	Stainless steel sheet (3 mm thickness)	17.5	40,000	700,000
2	All ISO 7089	1652	10	16,520
3	Stem/air generator (gas type)	1	3,000,000	3,000,000
4	Caster wheel	21	2,000	42,000
5	Gasket for flanges	20	1,000	20,000
6	Valves	20	1,000	20,000
7	O-rings	20	100	1,000
8	K-type thermocouple ($0\,^\circ C$–$1150\,^\circ C$)	1	40,000	40,000
9	Stainless steel pipe (5 mm thickness)	3	40,000	120,000
10	Pressure gauge	1	5,000	5,000
11	Pressure release valve	1	5,000	5,000
12	Thermochemical reactor Climber	1	150,000	150,000
13	Fabrication cost		500,000	500,000
14	Material transportation cost		100,000	100,000
15	500 kVA gas generator	1	80,000,000	80,000,000
16	Installation cost		200,000	200,000
17	**Total cost**			**84,919,520**
18	**Total cost of the 4 gasifiers**	**4**	**84,919,520**	**339,678,080**

The gasifier system will be serviced after every 200 h of operation. The requirements for servicing of the generator are as summarized in Table 2.

Table 2
Cost for gasifier service after every 200 h

S/N	Service type	Price
1	Servicing of injector pump and nozzle	8,000
2	25 L of engine oil	16,500
3	Gas filter	4,000
4	Oil filter	4,000
5	Washing of radiator	5,000
	Total	**37,500**

But the design is for 30 y, which is 262,800 h. To get the total 200 h, the generator will be serviced for 30 y, thus:

$$Total\ 200\ h\ in\ 30\ y = \frac{262,800}{200} = 1,314$$

Then, the total amount that will be spent for servicing of the generator in 30 y is:

$$Total\ amount\ for\ servicing\ of\ the\ generator\ for\ 30\ y = 1,314 \times 37,500 = 47,275,000\quad \text{Nigerian Naira}\ (\textbf{N})$$

NB: 1 USD = 360 Nigerian Naira.

References

Ahiduzzaman, M., Islam, A.K., 2009. Environmental impact of rice husk briquette fuel use in Bangladesh: a case study of Mymensingh. In: International Conference on the Developments in Renewable Energy Technology, vol. 1, pp. 1–4 (Dhaka, Bangladesh).

Akpan, U.S., Udoakah, Y.N., 2013. Electricity access in Nigeria: viability of off-grid photovoltaic system. In: AFRICON 2013: IEEE African Conference: Sustainable Engineering for a Better Future. Pointe-Aux-Piments, Mauritius, pp. 473–479. https://doi:10.1109/AFRCON.2013.6757778.

Asanka, S.R., Perera, S., 2014. Potential and viability of rice husk based power generation in Sri Lanka. J. Inst. Eng. 46 (4), 9–17. https://doi.org/10.4038/engineer.v46i4.6803. Sri Lanka.

Autodesk Knowledge Network, 2015. Inventor 2015 language packs. California, USA. https://knowledge.autodesk.com/support/inventor/downloads/caas/downloads/content/inventor-2015-language-packs.html. accessed 14 February, 2020.

Balestrino, A., Bassini, F., Pelacchi, P., 2007. On the control of a pyrolysis process. In: International Conference on Clean Electrical Power, IEEE, vol. 1, pp. 409–414 (Capri, Italy).

Gabbar, H.A., Aboughaly, M., Russo, S., 2017. Conceptual design and energy analysis of integrated combined cycle gasification system. Sustainability 9 (8), 1–18. https://doi.org/10.3390/su9081474.

International Energy Agency Report, 2014. World energy outlook 2014 electricity access database. Paris, France. http://www.worldenergyoutlook.org. accessed: Jan. 2019.

Kaundinya, D.P., Balachandra, P., Ravindranath, N.H., 2009. Grid-connected versus stand-alone energy systems for decentralized power – a review of literature. Renew. Sustain. Energy Rev. 13 (8), 2041–20150. https://doi.org/10.1016/j.rser.2009.02.002.

Kini, S.G., Chandrashekara, A.S., Radhakrishna, S.A., 2016. Power from rice husk for rice mills - a case study. International Research Journal of Engineering and Technology 405–409.

Mandelli, S., Jacopo, B., Riccardo, M., Emanuela, C., 2015. Off-grid systems for rural electrification in developing countries: definitions, classification and a comprehensive literature review. Renew. Sustain. Energy Rev. 58, 1621–1646. https://doi:10.1016/j.rser.2015.12.338.

Meisen, P., Akin, I., 2008. The Case of Meeting the Millennium Development Goals through Access to Clean Electricity. Global Energy Network Institute, p. p4. http://www.geni.org/globalenergy/research/meeting-mdgs-through-access-to electricity/MDG_Final_1208.pdf.

Nfah, E.M., 2013. Evaluation of optimal photovoltaic hybrid systems for remote villages in far north Cameroon. Renew. Energy 51, 482–488. https://doi: 10.1016/j.renene.2012.09.035.

Ohajianya, A.C., Abumere, O.E., Owate, I.O., Osarolube, E., 2014. Erratic power supply in Nigeria: causes and solutions. International Journal of Engineering Science Invention 3 (7), 51–55.

Okedu, K.E., Uhunmwangho, R., Promise, W., 2015. Renewable energy in Nigeria: the challenges and opportunities in mountainous and riverine regions. Int. J. Renew. Energy Resour. 5 (1), 222–229.

Okedu, K.E., Uhunmwangho, R., Odje, M., 2020. Harnessing the potential of small hydro power in Cross River state of southern Nigeria. Sustainable Energy Technologies and Assessments 37 (100617), 1–11. https://doi.org/10.1016/j.seta.2019.100617.

Oyejide, S.A., Adejumobi, I.A., Wara, S.T., Ajisegiri, E.S., 2014. Development of a grid-based rural electrification design: a case study of Ishashi and Ilogbo communities in Lagos state, south western Nigeria. J. Electr. Electron. Eng. 9 (4), 12–21. https://doi:10.9790/1676-09441221.

Pode, R., Diouf, B., Pode, G., 2015. Sustainable rural electrification using rice husk biomass energy: a case study of Cambodia. Renew. Sustain. Energy Rev. 44, 530–542. https://doi.org/10.1016/j.rser.2015.01.018.

Sambo, A.S., Garba, B., Zarma, I.H., Gaji, M.M., 2010. Electricity Generation and the Present Challenges in the Nigerian Power Sector. Energy Commission of Nigeria, Abuja-Nigeria, pp. 1–17.

Song, K.L., Paul, H.W., Lin, C.J., Ching, I.J., 1998. A process development for gasification of rice husk. Fuel Process. Technol. 55, 185–192. PII: S0378-3820(98)00049-6.

Ubwa, S.T., Abah, J., Oshido, B.A., Otokpa, E., 2014. Urea treated rice milling waste and its application as animal feed. Afr. J. Pure Appl. Chem. 8 (2), 23–31. https://doi.org/10.5897/AJPAC2013.0532.

Uhunmwangho, R., Okedu, K.E., 2009. Macro and micro hydropower: an option for socioeconomic development, case study-Agbokim Waterfalls, Cross River State, Nigeria. Pacific Journal of Science and Technology 10 (2), 529–534.

Uhunmwangho, R., Odje, M., Okedu, K.E., 2018. Comparative analysis of mini hydro turbines for Bumaji stream, Boki, Cross, River state, Nigeria. Sustainable Energy Technologies and Assessments 27, 102–108. https://doi:10.1016/j.seta.2018.04.003.

United States Agency for International Development, 2014. Hybrid Mini off Grids for Rural Elicitation: Lessons Learned, Alliance for Rural Electrification, vol. 1040. Renewable Energy House Rue d'Arlon, Brussels, pp. 63–65 (Belgium).