Techno-economic and Environmental Feasibility Analysis of Rice Husks fired Energy System for Application in a Cluster of Rice Mills

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Abstract

The agro-processing industries can play a critical role in the development of sustainable and clean energy systems. The lack of knowledge about the technical and economic viability of agro-waste to energy is a major barrier for successful implementation in developing countries, especially sub-Saharan Africa countries. This paper presents the techno-economic-environmental assessment of a cluster of rice mills located in Abakaliki, Nigeria, as a provider of clean energy. The cluster of rice mills can efficiently fulfil energy needs through the application of organic Rankine cycle based combined heat and power plant fired by the rice husk. Three scenarios of the plant were proposed and investigated for complete information. The rice husk from the cluster can provide daily 20–30MWh and 4–91MWh of electrical power and thermal power, respectively, at 14.5–21 % efficiency. A tonne of rice husk can provide 0.45–0.65 MWh of electricity; that the unit cost of electricity from the proposed system is between 0.12–0.159$/kWh, which is better than 0.947 US$/kWh for a diesel generator. About 270–483 kg of CO_2/MWh can be saved by the proposed combined heat and power system in relation to the current use of Lister diesel generators. The work also presents an appropriate business model for sustainable cottage rice processing industries.

Keywords: Rice Husk, Levelized cost of electricity, CHP ORC plant, Economic competitiveness

1 Introduction

The population of the world is growing steadily whereas the energy to sustain the socio-economic development is in deficit making a significant share of the world population live without clean energy [1]–[3]. Sub-Saharan Africa (SSA) has a fair share of the population living without clean energy, which has manifested in poor development progress [4]. The rural dwellings, which are mainly agrarian communities, are worst hit by the huge energy deficit. Nigeria has a population of about 170 million and comparatively very large primary energy potentials. The access to useful energy in Nigeria is poor and irregular; the access to the national grid is only about 10 % and 40 % of the rural dwellers and the urban dwellers, respectively [5], with a high duration of power outage [6]. The estimated electricity demand in the country is about 25,800 MW and the average daily peak supply is about 3,140 MW – 87.8% unsatisfied demand – with about 20% distribution/transmission loss [5], [7]. The country has witnessed a steady increase in

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electrification rate but the generation growth rate of 93 % over a 20-year horizon is an abysmal growth. For example, Indonesia and Bangladesh growth rates stood at 372% and 451%, respectively, in the same time horizon [8]. The power supply in Nigeria is also confronted with environmental challenges because the electricity generation landscape parades a significant proportion of fossil-driven energy conversion technologies (mainly natural gas and diesel); a share of over 80 % [8], [9]. The implication is that the country's current energy landscape is a handicap to meet some of the Sustainable Development Goals (SDGs) of the United Nations Development Programme (UNDP) in the interim and in the future because the SDG 7 (affordable and clean energy) has been identified as the enabler of the majority of the SDGs [10]–[13].

To guarantee the economic growth of dwellers living within the electricity non-connected areas in Nigeria, which feature an appreciable level of poverty and low economic status, sustainable and clean off-grid energy solutions are vital. Nigeria's, and other SSA nations', agro-industries have the potentials for cleaner energy development – namely agro-wastes (biomass). It is estimated that Nigeria has the potentials of generating about 700 TJ/year of energy from agro-wastes[13], with similar proportional estimates for other SSA nations [14]. The agro-wastes are mainly concentrated in the vicinity of the smallholder farms, which are normally concentrated in rural communities that have no access to energy. The implication is that agro-waste based clean energy solutions have to be sited near the agro-processing industry for social-economic benefits[14]. The current global emphases on energy solutions are decentralised and renewable energy sources because of the energy security and climate change mitigation[15]. The use of depleting and expensive fossil fuels comes with negative consequences like global warming potential (GWP) and greenhouse gas (GHG) emissions, which are responsible for climate change and its consequences like rising in sea level and loss of biodiversity[8], [16]–[20]. However, the potential for cleaner energy development, especially agro-wastes from the agro-processing industry, in the country remains efficiently unexploited.

The current focus of the Federal Government of Nigeria (FGN) is towards boost agricultural produce and food sufficiency, through the Agriculture Promotion Policy (2016-2020) of the Federal Ministry of Agriculture and Rural Development (FMARD) [21]. Rice production and processing is one of the current cardinal priorities of the country towards food sufficiency because rice is one of the major staple foods with a huge local production-demand gap in the country. As of 2016, the country imported 55 % of the country's rice demand [22]. However, the government is determined to reverse the local rice production-demand gap by vigorously implementing the FMARD's Agriculture Promotion Policy. The government's efforts towards local rice production has seen an increase in local rice production by 4% between 2016 and mid-year 2017 [22]. It is expected that with sustained policy and political will by FGN the rice production would experience a boom for local and export consumption[23]. The implication is that wastes associated with rice production and processing would increase proportionally, with the consequences of negative multiplier effects on the environment and ecosystem arising from indiscriminate dumping and burning of residues, and environmental mismanagement. Fig. 1 shows a typical heap of rice husks (RH) at a cluster of rice mills located at a site in Abakali, Nigeria. The operators of the cluster are burdened with the immediate evacuation of the RH heaps to reclaim space for continuous business. Occasionally, the RH heaps are burnt in open-air during the dry season with the consequence of increasing GHG and other harmful gases without the corresponding energy utilisation. It is, therefore, expedient to harness the energy in the RH to useful energy production, as being demonstrated in many other countries[8], [14], [19], [24]–[27].

Figure 1 RH heap in a cluster of rice mills in Abakaliki, Ebonyi State, Nigeria

There exist three fundamental methods for the conversion of biomass (RH in this case) into other forms of energy carrier, namely gasification, bio-digestion (anaerobic) and direct combustion[19], [25], [28]–[30]. The conversion of biomass to useful energy could be sustained by means of direct combustion of the biomass and internal combustion of products of gasification and bio-digestion of biomass. The gasification technology involves the conversion of biomass into a combustible gas via its partial oxidation at high temperatures in the range 800–900 ^oC, which requires external energy sources to provide the required temperature[31]. The technology for RH gasification is still in progress with few available commercial projects[19], [32]. The RHs gasification may be limited by the technical capacity of up to 0.5MW, with corresponding high investment cost per unit of power produced, over the power plants fired by direct combustion[25], [33]. The bio-digestion (anaerobic) technology involves the conversion of the biomass feedstock to gas products (mainly methane and carbon dioxide) by bacterial in the absence of free oxygen. The energy content of the combustible gas from the bio-digestion technology is about 20-40 % of the lower heating value of the feedstock. Anaerobic technology is a commercially proven technology, but it requires a high level of investment at a large scale [31]. The direct combustion of biomass invoove the combustion of biomass feedstocks in a well-aerated combustor to produce hot flue gases, which can be used in other conversion technologies to produce up to 3000 MW power [31]. The technology for direct combustion of RHs for the generation of power (electricity and heat) has attained an established technology maturity [18], [26], [32]; with over 257 biomass-fired ORC plants (Turboden® technology) currently in operation[24]. The organic Rankine cycle (ORC) is well-suited for agro-waste-to-electrical energy technologies since its operational regimes are adequate for the conversion of low-temperature grade energy. The ORC is a well-established technology for combined-heat-and-power (CHP) systems for an electrical power output of up to 2MW; a condition which renders the steam Rankine cycle technically and economically unattractive. The biomass-fired ORC plant has the potential to solve the tri-lemma (affordability, availability and environmental protection) surrounding the adoption of cleaner energy for rural electrification [27], [34]–[37]. Whilst conventional energy systems will remain important for Nigeria's energy mix, biomass-to-electrical energy systems also offer new possibilities for areas where access is low and supply is unreliable[38].

The aim of this paper is to present the techno-economic and environmental investigation of an RH-fired ORC CHP energy system for a rice processing site in Nigeria along with an appropriate business model. In the present context, techno-economic means the linkage of a system's technical parameters to financial metrics within some imposed technical and economic inputs and constraints (factors). In this light, the current investigation is focused on Small Power Production (SPP) to meet the energy demand of a cluster of rice mills and nearby rural dwellers by utilising the rice husk wastes as the primary source of energy. Specifically, the focus is on technology readiness, economic sustainability and environmental impact of an RH-fired ORC plant to provide affordable and clean energy for agro-processing industries and agrarian rural communities[20]. The outcome will provide evidence for the development of alternative SPP plants in the pursuit of making agro-industries competitive, and supply sufficient, affordable and clean energy to the rural communities in Nigeria.

2 Methodology

The methodology adopted in this paper is divided into four major components, as shown in the framework in Fig. 2. The research framework is intended for order and ease of adaptation of the research methodology. The research framework is fashioned to promote the input-output relationship as the outputs from a phase form the inputs of subsequent phases. Section 2.1 presents the proposed system's boundary and configuration. Section 2.2 is on the assessments of a biomass energy resource (RH) and energy load demand of the cluster of rice mills, which gives input to the technical feasibility study, financial pre-feasibility studies and environmental sustainability analysis, as presented in Section 2.3. Section 3.4 is on sensitivity analysis, which emphasises the competitiveness of the proposed energy system in the light of technical, economic and policy parameters. The sensitivity analysis is followed by a proposed business and energy model (BEM), presented in Section 4. The coloured arrows show the flow of information in the methodology.

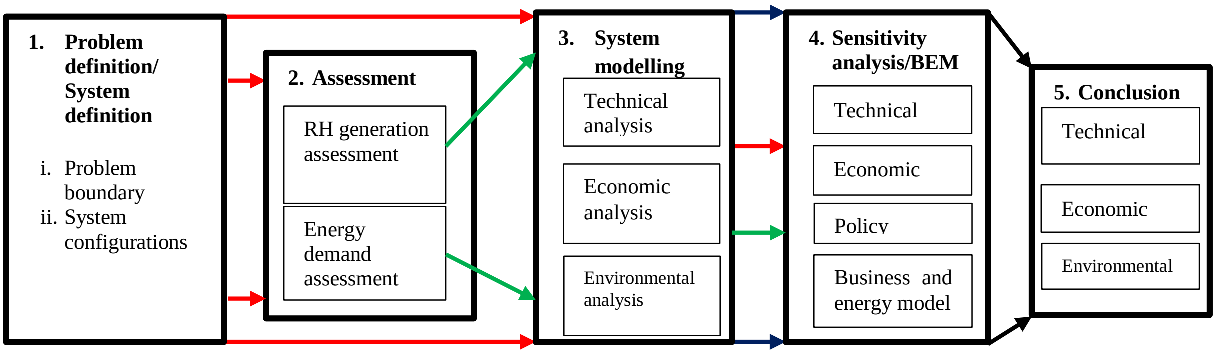

Figure 2 Research methodology framework

2.1 Boundary and system description

The research boundary is limited to a cluster of local rice mills located at Ogoja Road, Azuiyi Udene in the suburb of Abakaliki town (latitude: 6.32 ^{o}N and Longitude: 8.12 ^{o}E), the state capital of Ebonyi state, in the South-East geopolitical zone of Nigeria. Abakaliki has a population of about 775,604 inhabitants. Abakaliki parades other local milling centres; however, the Abakaliki cluster of rice mills is prominent because it houses 356 units of local rice mills operated by local millers within a radius of about 210 meters. The cluster of rice mills is owned and managed by agro-business individuals and cooperative societies. Rice out-growers from far and near bring their unprocessed rice produce for milling in the cluster of rice mills ; the cluster also forms a market where people buy and sell processed rice. The cluster has a pocket of warehouses where unprocessed rice are stored during the season of rice harvesting. The unprocessed rice is transported to the milling cluster by rice merchants and processed within the cluster. The husks generated in-situ are dumped in a specific area within the cluster, which does not require further transportation of the rice husks – it implies zero transportation cost. Occasionally, the mills are gutted by fire due to the uncontrolled combustion of the rice husks within the cluster, which has resulted in the loss of properties and bodily injury. Currently, each unit of rice mill generates its own power from inefficient Lister diesel generators with heavy emissions that pollute the environment. The heavy emissions of CO_2, toxic flue gases and particulate matters may be responsible for some of the health challenges associated with the mill operators. Therefore, a central sustainable energy system is proposed to meet the energy demand (both electrical and thermal energy) of the Abakaliki cluster of rice mills instead of the current energy supply system, which is based on a disaggregated energy supply from the inefficient and polluting diesel generators.

The proposed CHP energy system is schematically presented in Fig. 3. The system comprises a biomass combustor (A), heat transfer fluid heat-exchanger (B), evaporator (C), expanders (D), evaporator-condenser unit ($E - C$), pumps (F, G), recuperator (H), condenser (E) and post-heat-exchanger (I). Three scenarios of a CHP energy system are proposed in the present study; the scenarios are schematically presented in Fig. 3. The three scenarios are based on system configurations and operation strategy. The configurations are simple Organic Rankine Cycle (ORC) combined-heat-and-power (CHP) plant and cascade ORC CHP plant. The operation strategy is based on the cascade ORC CHP system – to use the cascade ORC CHP continuously and the option to operate it intermittently (5 hours a day according to the operational hours of the cluster of rice mills).

Simple ORC CHP: The RH is combusted in A and the internal of the flue gases is transferred to the heat transfer fluid (HTF) in B. The heat transfer fluid used is Globaltherm Omnitech, with a non-degradable operating temperature of up to 400 °C[39]. The internal energy in the HTF is transferred to the working fluid (toluene), which converts it to vapour in C; the high pressure and temperature vapour of the working fluid from C is expanded in the upper expander ($\mathrm{D_U}$) to generate electrical energy. The saturated vapour fluid exiting $\mathrm{D_U}$ is condensed in the condenser, E, and pumped into C at the evaporator's operating pressure. Process water is used to condense the working fluid from $\mathrm{D_U}$ in the condenser-evaporator unit, $E - C$, which is then heated up by the flue gas in I for heating purposes. Process $7 - 8 - 9$ features the simple ORC thermal energy generation; whereas process $1 - 2 - 3 - 4 - 1$ features the simple ORC electrical energy generation.

Cascade ORC CHP: In the cascade configuration, a lower ORC plant (bottoming cycle) running on R113 as the working fluid, is coupled to the upper ORC (topping cycle) through the condenser-evaporator unit ($E - C$). The R113 is known to manifest better thermodynamic performance under low-temperature heat recovery for ORC applications [40], [41]. The working fluid (Toluene) in the topping cycle condenses by rejecting heat to the working fluid in the bottoming cycle to evaporate its working fluid (R113); it is then expanded in the lower ORC expander ($\mathrm{D_L}$) to generate electrical energy. The working fluid that is leaving $\mathrm{D_L}$ communicates thermally with the working fluid that is leaving the pump ($\mathrm{F_L}$) in the recuperator for improved efficiency. Process $7 - 8' - 9$ features the cascade ORC thermal energy generation; whereas processes $1 - 2 - 3 - 4 - 1$ and $1' - 2' - 2'' - 3' - 4' - 4'' - 1'$ features the cascade ORC electrical energy generation. It might be argued that toluene is considered a polluting fluid, but it is envisaged that maximum safety and handling procedures of the working fluids would be adhered to at all times. However, toluene is not acutely toxic and is considered readily biodegradable. Furthermore, toluene can quickly be degraded by the photo-oxidation process in the atmosphere [42]. From the technical perspective, many works in the public domain show that toluene is a good choice for recovering high-temperature heat sources. Specifically, for ORC operations, toluene is considered as one of the two most suitable working fluids out of fifty-two screened working fluids in terms of maximum power output and exergy efficiency, please see [43], [44].

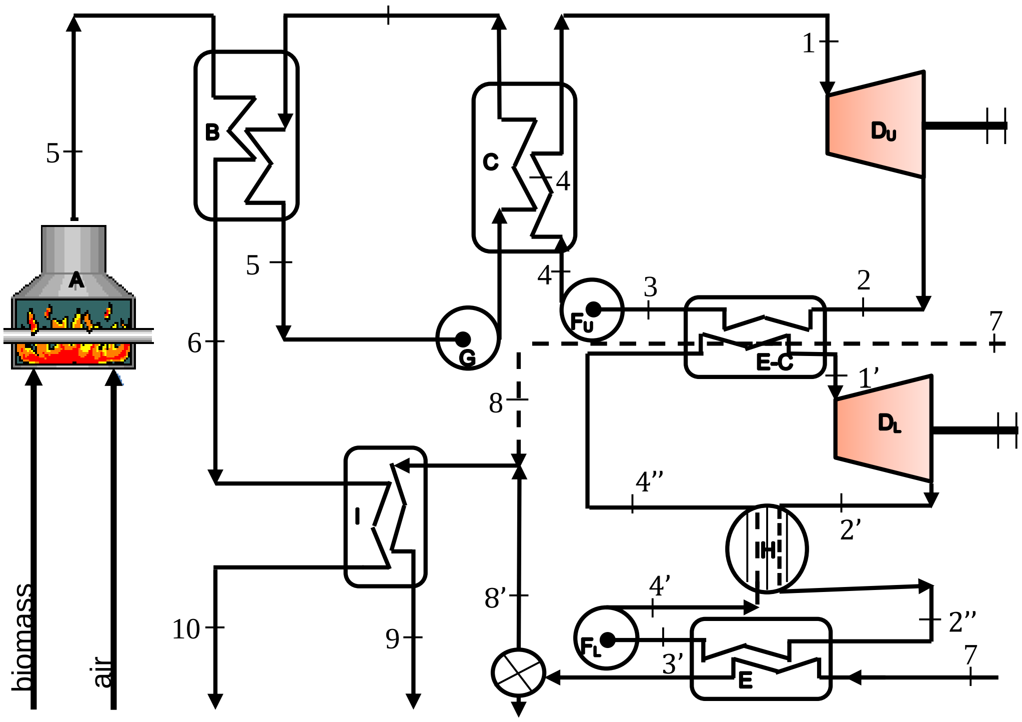

Figure 3 Schematic diagram of the proposed CHP system

2.2 Assessment

The assessment is on the quantity of RH and the energy demand of the Abakaliki cluster of rice mills. The milling operation starts at 9:00 am and ends at 1:00 pm (4 hours) daily, and followed by 2 hours of *de-stoning* operation.

2.2.1 RH assessment

The Abakaliki cluster of rice mills has 356 units. A unit has the capacity of processing an average of nine bags of unprocessed rice per day (about 20.41kg of rice per bag), which amounts to 183.69 kg/h milling capacity. The RH-to-product (rice grain) weight ratio was estimated at 0.23. The implication is that the cluster has the capacity of generating 60.17 tonnes of husk per day (2507.08 kg per hour). The RH moisture content and lower heating value (LHV) presented in Arranz-piera et al. [14] can be adopted in the current study on the basis of the similarity in cultivation practice and climatic condition. Therefore, the available RH for fuel is 0.54 kg per second; this is the available dried feedstock. Seasonal variability on the daily capacity of processed rice is insignificant since excess unprocessed rice is kept in a warehouse during the season of plenty and processed during the offseason.

2.2.2 Energy demand assessment

The rice processing starts with parboiling (soaking and steaming) of the rice, which is done by the use of firewood; it is followed by uncontrolled open sun drying of the parboiled rice; thereafter, the milling follows; and finally, the *de-stoning* of the milled rice. The three hundred and fifty-six (356) milling units are powered by lister diesel generators – three hundred and forty-three (343) 16 hp diesel engines and thirteen (13) 26 hp diesel engines. The diesel engine electrical efficiency is adopted as 37 % according to Jakhrani et al. [45]. There are twelve *de-stoning* machines, each is rated 7.64 hp. There are 75 incandescent light bulbs (rated 60 W and 100 W) mainly for security lighting purposes. The energy demand profile of the cluster is shown in Fig. 4; with daily electrical energy demand and peak power of 6.66 $\mathrm{MWh_{el}}$ and 1.61 MW, respectively. The energy demand assessment was limited to the electrical energy demand; however, it has been established that the ratio of electrical energy to thermal energy in rice processing is about 1:9 for parboiled rice[46], [47]. Therefore, the daily thermal energy demand can be assumed as 60 $\mathrm{MWh_{th}}$. It was observed that there would be a significant reduction in the energy demand once proper energy efficiency management is adopted since inefficient local types of machinery are used in the cluster.

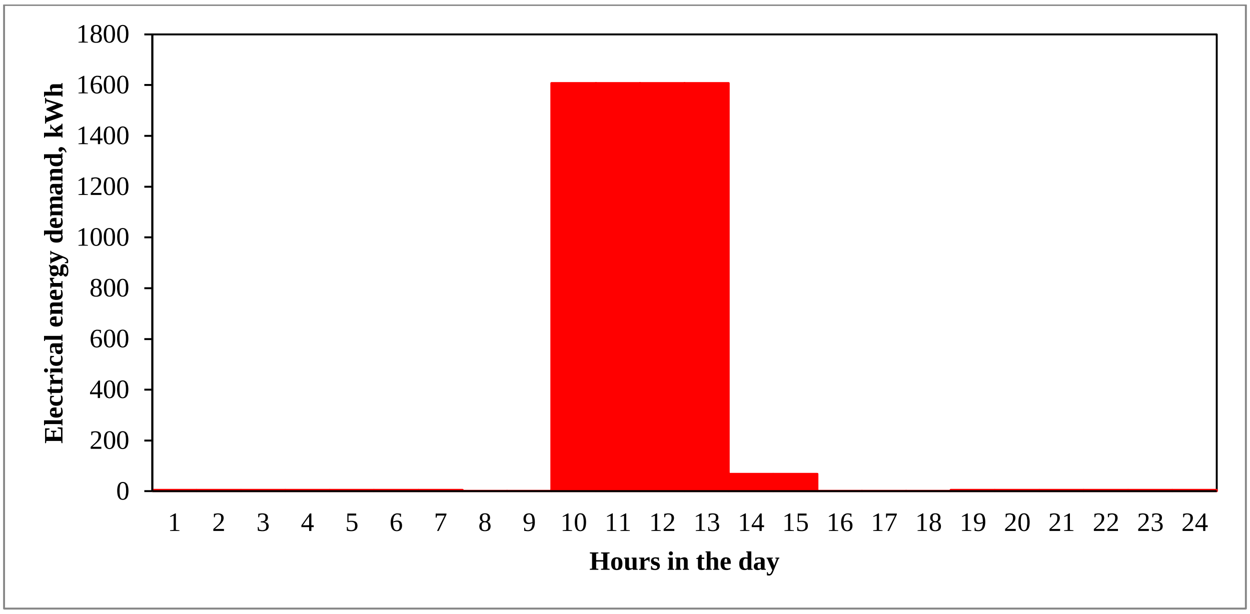

Figure 4 Abakaliki cluster of rice mills electrical energy demand profile

2.3 Modelling

The modelling follows the system description presented in Section 2.1. The energy analysis is based on the first law of thermodynamics presented in Eq. (1)[48]:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \Sigma_{in}\left\{\dot{m}\left(h + \frac{v^2}{2} + gz\right)\right\} - \Sigma_{out}\left\{\dot{m}\left(h + \frac{v^2}{2} + gz\right)\right\} \tag{1}$$

where $dE\ (kJ)$ is change in energy, $dt(s)$ change in time, $\dot{Q}(kW)$ is heat transfer, $\dot{W}(kW)$ is work transfer, $\dot{m}(kg)$ is mass flow rate, $h(kJ/kg)$ is specific enthalpy, $v(m/s)$ is velocity, $g(m/s^2)$ is the acceleration due to gravity and $z(m)$ is elevation.

The assumptions that kinetic and potential energies are negligible, the process operates at a steady-state and negligible heat loss are considered in the application of Eq. (1).

2.3.1 Technical analysis

The general chemical equation for combustion stoichiometry of biomass can be presented according to Eq. (2) [49], which is appropriate for RH combustion since the percentage compositions of Nitrogen and Sulphur in RH are not significant [50].

$$C_xH_yO_z + \left[x + \frac{y}{4} - \frac{z}{2}\right](O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76\left(x + \frac{y}{4} - \frac{z}{2}\right)N_2 \qquad (2)$$

The ultimate analysis of RH presented in Madhiyanon et al. [50] is considered in the present analysis. The fuel-air ratio can be obtained from Eq. (2) accordingly as [51]:

$$r_{f/a} = \frac{m_{f-stoi}}{m_{a-stoi}} = \frac{\bar{M}_f}{4.76\left(x+\frac{y}{4}-\frac{z}{2}\right)\bar{M}_a} \qquad (3)$$

where $m_{f-stoi}(kg)$ and $m_{a-stoi}(kg)$ are the masses of fuel and air, respectively, for complete combustion; whereas $\bar{M}_f(kg/kmol)$ and $\bar{M}_a(kg/kmol)$ are the molecular weight of fuel and air ($\bar{M}_a \approx 28.84kg/kmol$).

However, the majority of biomass combustors operate under excess air condition (lean combustion), with a percentage excess air, $\alpha_{air}(\%)$, which can be estimated according to [51]:

$$\alpha_{air} = 100\left(\frac{m_a}{m_{a-stoi}} - 1\right) \equiv 100\left(\frac{1}{r_{eq}} - 1\right) \qquad (4)$$

The actual fuel-air ratio is, therefore, given as

$$r'_{f/a} = r_{eq}r_{f/a} \qquad (5)$$

The expected maximum combustion temperature, $T_{ad}(K)$, of the combustion products (the flue gases), which is known as the adiabatic flame temperature, can be theoretically estimated as [51]:

$$T_{ad} = \begin{cases} \eta_{com}\left[T_R + \frac{r'_{f/a}LHV}{(1+r'_{f/a})\bar{c}_{p,P}}\right] \; for \;\; r_{eq} \le 1 \; (lean \; combustion) \\ \\ \eta_{com}\left[T_R + \frac{r_{f/a}LHV}{(1+r'_{f/a})\bar{c}_{p,P}}\right] \; for \;\; r_{eq} < 1 \; (rich \; combustion) \end{cases} \qquad (6)$$

where $\bar{c}_{p,P}(kg/kJK)$ is the average specific heat capacity of the combustion products at constant pressure and $\eta_{com}(-)$ is combustor efficiency associated with heat transfer loss and dissociation of products at elevated temperature (η_{com}~0.85 is adopted as regard the boiler efficiency[52]). It is expected that heat transfer loss in the combustor due to combined actions of conduction, radiation and convection is imminent. However, we assumed that heat transfer loss in the other components of the proposed systems is negligible due to adequate lagging of the piping and steady state operations.

The mass of the flue gases, $\dot{m}_{flue}(kg/s)$, can be computed as

$$\dot{m}_{flue} = \dot{m}_f\left[(1-\beta) + \frac{1}{r'_{f/a}}\right] \qquad (7)$$

where β is the fraction of ash in the fuel, and $\dot{m}_f \equiv \dot{m}_{f-stoi}$, on dry mass basis, which is the current case. The mass flow rate of the heat transfer fluid (thermal oil), $\dot{m}_{htf}(kg/s)$, is obtained on the basis of energy balance, Eq. (1), on the heat transfer fluid heat-exchanger as follows

$$\dot{m}_{htf} = \frac{\dot{m}_{flue}\bar{c}_{p,flue}(T_5-T_6)}{\bar{c}_{p,htf}(T_{5'}-T_{6'})} \qquad (8)$$

Simple CHP ORC cycle

The mass flow rates of the working fluid, $\dot{m}_{wf,U}(kg/s)$, and process water, $\dot{m}_{w,U}(kg/s)$, are obtained, based on the application of the first law of thermodynamics, Eq. (1), on the evaporator and condenser, respectively, as

$$\dot{m}_{wf,U} = \frac{\dot{m}_{htf}\bar{c}_{p,htf}(T_{5'}-T_{6'})}{h_1-h_4}, \text{ and} \tag{9}$$

$$\dot{m}_{w,U} = \frac{\dot{m}_{wf}\{h_1-(h_1-h_2)\eta_{is,ex}-h_3\}}{\bar{c}_{p,w}(T_8-T_7)}; \tag{10}$$

$$\text{with } T_8 = T_3 - \Delta T_2 \tag{11}$$

where $\Delta T_2(K)$ is the pinch temperature in the condenser unit and $\eta_{is,ex}(-)$ is the expander isentropic efficiency.

The condenser heat load, $\dot{Q}_{ev,U}(kW)$, is computed as

$$\dot{Q}_{ev,U} = \dot{m}_{wf,U}(h_1 - h_4) \tag{12}$$

The power generated by the expander, $\dot{W}_{ex,U}(kW)$, is computed as

$$\dot{W}_{ex,U} = \eta_{ex}\eta_{is,ex}\dot{m}_{wf,U}(h_1 - h_2) \tag{13}$$

where $\eta_{ex}(-)$ is the overall expander efficiency, which accounts for both mechanical and electrical losses

The power rating of the recirculation working fluid pump, $\dot{W}_{p,rwf,U}(kW)$, can be obtained as follows

$$\dot{W}_{p,rwf,U} = \frac{\dot{m}_{wf,U}\times(h_4-h_3)}{\eta_p} \tag{14}$$

The power rating of the heat transfer fluid pump, $\dot{W}_{p,htf}(kW)$, is computed as

$$\dot{W}_{p,htf} = X_{pf}\dot{m}_{htf} \tag{15}$$

where X_{pf} is the pump fraction, it is an adjustable parameter ~4.91 [28].

The net power or the power that benefits, $\dot{W}_{net,U}(kW)$, can be computed according to Eq. (16)

$$\dot{W}_{net,U} = \dot{W}_{ex} - \left(\dot{W}_{p,rwf,U} + \dot{W}_{p,htf}\right) \tag{16}$$

The useful heat extracted, $\dot{Q}_{uhe,U}(kW)$, from the combined heat and power (CHP) system can be obtained as follows

$$\dot{Q}_{uhe,U} = \dot{m}_w\left[\bar{c}_{p,w7\_8}(T_8 - T_7) + \bar{c}_{p,w8\_9}(T_9 - T_8)\right] \tag{17a}$$

$$\text{where } T_9 = T_8 + \frac{\dot{m}_{flue}\bar{c}_{p,flue}(T_6-T_{10})}{\dot{m}_{w,U}\times\bar{c}_{p,w8\_9}} \tag{17b}$$

The first and second laws efficiency for the plant (based on electrical power generation) are obtained, respectively, as

$$\eta_{I,ORC} = \frac{\dot{W}_{net,U}}{\dot{m}_f LHV}, \text{ and} \tag{18}$$

$$\eta_{II,ORC} = \eta_{I,ORC}\Big/\left(1-\frac{T_3}{T_1}\right) \tag{19}$$

The overall system's first law and second laws of thermodynamics are obtained, respectively, as

$$\eta_{I,CHP} = \frac{\dot{W}_{net,U}+\dot{Q}_{uh,U}}{\dot{m}_f LHV}, \text{ and} \tag{20}$$

$$\eta_{II,ORC} = \eta_{I,CHP}\Big/\left(1-\frac{T_7}{T_5}\right) \tag{21}$$

The heat recovery factor, which is the percentage of the energy released from the fuel that is recovered to serve a thermal load, can be computed as follows

$$f_{hr} = \frac{\dot{Q}_{uhe,U}}{\dot{m}_f LHV} \times 100 \tag{22}$$

Cascade CHP ORC cycle

The mass flow rate of the working fluid in the lower ORC plant, $\dot{m}_{wf,L}(kg/s)$, and the mass flow rate of the cooling water, $\dot{m}_{w,cooling,cs}(kg/s)$, and process water, $\dot{m}_{w,process,cs}(kg/s)$, can be calculated, respectively, as

$$\dot{m}_{wf,L} = \frac{\dot{m}_{wf,U} \times \left(h_1 - (h_1 - h_2)\eta_{is,ex} - h_3\right)}{h_{1\prime} - h_{4\prime}}, \tag{23}$$

$$\dot{m}_{w,cooling,cs} = \frac{\dot{m}_{wf,L}(h_{2\prime\prime} - h_{3\prime})}{\bar{c}_{p,w}(T_{8\prime} - T_{7\prime})} \text{ and} \tag{24}$$

$$\dot{m}_{w,process,cs} = \frac{\dot{m}_{flue}\bar{c}_{p,flue} \times (T_6 - T_{10})}{\bar{c}_{p,w}(T_9 - T_{8\prime})} \tag{25}$$

The power output, $\dot{W}_{ex,L}(kW)$, pump work, $\dot{W}_{p,rwf,L}(kW)$, and the net power output, $\dot{W}_{net,L}(kW)$, in the lower ORC plant are calculated, respectively, as follows

$$\dot{W}_{ex,L} = \eta_{ex}\eta_{iex}\dot{m}_{wf,L}(h_{1\prime} - h_{2\prime}), \tag{26}$$

$$\dot{W}_{p,rwf,L} = \frac{\dot{m}_{wf,L} \times (h_{4\prime} - h_{3\prime})}{\eta_p} \text{ and} \tag{27}$$

$$\dot{W}_{net,L} = \dot{W}_{ex,L} - \dot{W}_{p,rwf,L} \tag{28}$$

The overall net power output, $\dot{W}_{net,cs}(kW)$, of the cascade ORC CHP plant can be obtained as

$$\dot{W}_{net,cs} = \dot{W}_{net,U} + \dot{W}_{net,L} \tag{29}$$

The cascaded cycle thermal and second law efficiencies (based on electrical power generation) are obtained as

$$\eta_{I,ORC,cs} = \frac{\dot{W}_{net,cs}}{\dot{m}_f LHV}, \text{ and} \tag{30}$$

$$\eta_{II,ORC} = \eta_{I,ORC,cs} \Big/ \left(1 - \frac{T_{3\prime}}{T_1}\right) \tag{31}$$

The process water thermal energy, $\dot{Q}_{uhe,cs}(kW)$, in the cascaded system can be estimated as follows

$$\dot{Q}_{uhe,cs} = \dot{m}_{w,process,cs}\bar{c}_{p,w}(T_9 - T_{8\prime}) \tag{32a}$$

$$\text{where } T_9 = T_{8\prime} + \frac{\dot{m}_{flue}\bar{c}_{p,flue}(T_6 - T_{10})}{\dot{m}_{w,L} \times \bar{c}_{p,w8\prime\_9}} \tag{32b}$$

The overall cascaded system's first law and second laws of thermodynamics are obtained, respectively, as

$$\eta_{I,CHP,cs} = \frac{(\dot{W}_{net,cs} + \dot{Q}_{uh,cs})}{\dot{m}_f LHV}, \text{ and} \tag{33}$$

$$\eta_{II,ORC,cs} = \eta_{I,CHP,cs} \Big/ \left(1 - \frac{T_7}{T_5}\right) \tag{34}$$

In the case of Eqs (19) and (31) the second law efficiency is defined to compare the closeness of the thermal efficiency of the three CHP scenarios to the Carnot cycle efficiency for the production of work (electricity) only; whereas for Eqs (21) and (34), the second law efficiency is defined to compare the closeness of the thermal efficiency of the three CHP scenarios to the Carnot cycle efficiency for the simultaneous production of work and heat.

The heat recovery factor, $f_{hr,cs}(\%)$, which is the percentage of the energy released from the fuel that is recovered to serve a thermal load, can be computed as follows

$$f_{hr,cs} = \frac{\dot{Q}_{uh,cs}}{\dot{m}_f LHV} \times 100 \tag{35}$$

2.3.2 Economic Analysis

The Net Cost (NPC), in USD, of the CHP system, which is the aggregated expenses incurred in present term by the plant throughout the life cycle, also known as the Life Cycle Cost (LCC), can be obtained as

$$NPC = \sum_q^5 C_q \, ; q \in \{1,2,3,4,5\} \equiv \{Combustor, HXs, Pump, Expander, O\&M\} \tag{36}$$

where C (USD), HXs and $O\&M$ stand for cost, heat exchangers and, operation and maintenance.

$$C_{O\&M} = C'_{O\&M} + \sum_{j=2}^{N} C'_{O\&M}(1+i)^{-j} \tag{37}$$

where $C'_{O\&M}$ (USD) is the annual cost of operation and maintenance.

The Annualised Life Cycle Cost (ALCC) of the plant can be computed from the NPC (USD) by considering the capital recovery factor, $F(i,N)$, as follows [53]

$$ALCC = F(i,N)NPC \tag{38}$$

The capital recovery factor can be evaluated by:

$$F(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{39}$$

The Levelized cost of electricity (LCOE), which represents the average cost per kWh (USD/kWh) of the electrical energy generated by the system, can be calculated as;

$$LCOE = \frac{ALCC}{(\dot{W}_{net,el})C_f} \tag{40}$$

The break-even point (BEP), in years, as presented in Ee.(41), can also be used to measure the economic merit of energy systems. It measures the number of years the venture will take to fully recover invested costs.

$$BEP = \frac{C_{INV}}{(\dot{W}_{net,el})C_f UEC} \tag{41}$$

where C_{INV} and UEC (USD/kWh) are the initial investment cost and the reference cost of electricity, respectively.

It is necessary to establish the capital cost of an ORC plant to do the economic analysis. The available data in the open domain suggests that the unit cost (USD/kW) of a biomass direct combustion CHP ORC could be estimated by Eq.(42), based on the available data from the literature and leading manufacturers[14], [19]. The maintenance cost of 97.45 \$/kW/year is adopted from [14], and labour cost is 30 \$/kW/year (estimated on cross-comparison with the existing thermal power plants in the country); therefore, the operation and maintenance of the plant could be estimated at 127.45\$/kW/year. The CHP ORC plant is assumed to have 20 years of useful life.

$$C_{ORC} = \sum_{j=1}^{2} 36390(1+\omega)\left(\dot{W}_{ex,j}\right)^{-0.244} ; j \in \{1,2\} \equiv \{Upper\ cycle, lower\ cycle\} \tag{42}$$

where $\omega \epsilon [0,1]$ accounts for the import tariff, which is associated with the importation of the plant's components. It should be noted that the cost analysis does not consider the cost of land because it is envisaged that the current land occupied by the inefficient and polluting rice mills would be transferred to the proposed plant at zero cost. Furthermore, zero cost is also attached to the transportation of the rice husks because they are produced in situ, which does not require further transportation.

2.3.3 Environmental Analysis

The current focus of the paper is on climate change mitigation by reducing greenhouse gases in agroindustry, rice processing in this case. The implication is that the impact of the toxicity of the ash on the environment is outside the scope of the current study. However, we have developed a concrete business model (please, see Section 4), that will make use of the ash from the rice husks post-combustion, e.g. cement-based materials [42]. Biomass fuelled power plants have the potentials of driving a carbon-neutral economy; plant (tree, crop, etc.) growth is sustained by the carbon dioxide emitted during the biomass combustion – net-zero carbon dioxide emission[54]. The amount of potential CO_2 emission savings, ε_{CO_2}, that can be achieved by substitution of fossil fuels with biomass can be computed by Eq. (43) [19].

$$\varepsilon_{CO_2,i} = \left(\frac{\eta_{I,CHP,j} - \eta_{I,ORC,j}}{\eta_{boiler}}\right) E_R + \eta_{I,ORC,j} E_F;\ j = simple, cascaded \tag{43}$$

where η_{boiler} is the boiler efficiency or the combustor efficiency, E_R is the reference emission factor for energy generation from fossil fuels ($kgCO_2/MWh$) and E_F is the emission factor for the production of electricity ($kgCO_2/MWh$).

The typical emission factors and efficiency parameters for the competing fossil-fuelled electricity generation thermal power plants are presented in Table 1.

Table 1. Typical emission factors and efficiency parameters

Fuel	System	Electrical efficiency, %	Boiler efficiency, %	E_F $kgCO_2/MWh$	E_R $kgCO_2/MWh$
Natural gas[1]	gas turbine	44.4	90	518	202
Diesel[2]	diesel generator	37	98*[55]	1270	446

[1] data extracted from [19]; [2] data extracted from [45]

*combustor efficiency is considered as the boiler efficiency for the diesel generator

3 Results and discussion

The results presented are based on the three scenarios considered in the study. Outputs from the resource assessment serve as some of the input data for the technical, economic and environmental analyses. Other pertinent input data are presented in Table 2.

Table 2. Assumed data for system analysis

S/No	Quantity	Units	Value	Reference

1	lower heating value of RH	kJ/kg	13035	[14]
2	RH moisture content	%	30	[14]
3	ash content in rice	%	24.30	[14]
4	specific heat capacity of flue gases	kJ/kg.K	1.0614	[56]
5	percentage excess air for combustion	%	30	[50]
6	pinch temperature	°C	5	[52]
7	boiler efficiency	%	85	[52]
7	overall expander efficiency	%	85	[26]
8	isentropic efficiency	%	95	[52]
9	pump efficiency	%	75	[18]
10	internal heat exchanger efficiency	%	95	[26]
11	ambient temperature	°C	27	-
12	final temperature of flue gases	°C	30	-
13	system life cycle	year	20	[25]
15	fuel cost	$/year	120	-
16	effective interest rate	%	9*	[57]
17	plant capacity factor	hour	7500	[14]

*ten years (2007-2016) historic average [57]

3.1 Results of technical analysis

The computed flue gas temperature, the source of energy for the proposed plants, is 825 °C at 101.325 kPa combustor pressure (the combustion process is naturally aspirated). Table 3 presents the pertinent design parameter for the three CHP ORC design scenarios. It is shown that the cascade CHP plant peak electrical power is 43 % more than the simple CHP peak electrical power; conversely, the cascade CHP peak thermal power is 95 % less than the simple CHP peak thermal power at a process water temperature of 96.5 °C. This is expected since the simple CHP heat recovery factor is 62.1% as against 3.1% of the cascade CHP. The daily electrical energy generation of all the three CHP scenarios are well above the daily electrical energy demand of the Abakaliki cluster of rice mills; in excess of 215%, 350% and 248% for simple CHP, cascade continuous and cascade intermittent, respectively. The excess electrical energy could serve the nearby households and businesses once an optimal small power production business model is established. However, no scenario is able to meet the peak electrical demand of 1.61MW; with a shortfall of 36.6% and 9.3% for simple CHP and cascade CHP, respectively. It is observed that the cascade continuous scenario has better RH utilisation in terms of electrical energy, with available electrical energy per tonne of RH of 0.65 MWh$_{el}$; followed by the cascade intermittent and least by the simple CHP. The simple CHP available electrical energy per tonne of RH is 0.45 MWh$_{el}$, which compares well with ~0.5MWh$_{el}$/tonne presented by Pode et al. [58] for the simple ORC plant.

Table 3. Technical parameters at design conditions

technical parameter	system configuration		
	simple CHP	cascade continuous	cascade intermittent
available peak thermal power (MW)	4.370	0.216	0.216
available peak electrical power (MW)	1.021	1.460	1.460
pumping work (MW)	0.073	0.077	0.077
available daily electrical energy (MWh_{el})	20.98	30	23.17
available daily thermal energy (MWh_{th})	91.42	4.44	69.03
heat recovery factor (%)	62.09	3.08	3.08
available electrical energy per ton of RH (MWh_{el}/tonne)	0.453	0.648	0.500
available energy per ton of RH (MWh/tonne)	2.42	0.744	1.99
process water maximum temperature (°C)	96.5	96.5	96.5

Fig. 5 shows thermodynamics figures of merit for the three scenarios. The simple ORC scenario has electrical efficiency and overall system efficiency of 14.5 % and 78.3 %, which are in a good agreement with values of 14.6 % and 79.9 %, respectively, reported by Foresti et al. (2019) [26]. Furthermore, the efficiency of the three CHP scenarios falls within 14.5 - 20.79 %, as shown in Fig. 5, which also compare well with the efficiency values of 12.8-19.9 % presented by Situmorang et al. (2021) [42] for benzene operated ORC CHP. The cascade electrical efficiency is 43% more than the simple ORC plant. However, the simple CHP has the best overall system efficiency (CHP) because it generates more thermal energy and no second mechanical-to-electrical loss since no second expander, which is also manifested in the second law efficiency.

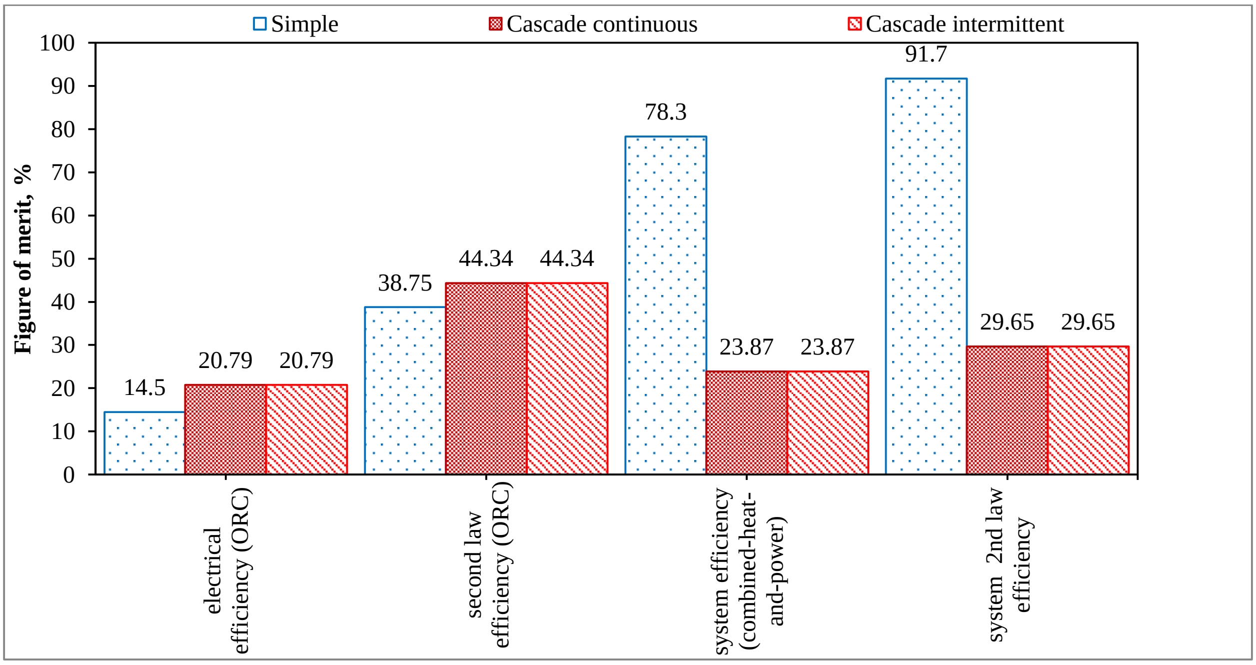

Figure 5 Technical figure of merits

3.2 Results of economic analysis

The results of the economic analysis are limited to electrical energy generation since there are no available process systems for the direct utilization of the thermal energy generated without further cost implications. For example, the utilisation of the thermal energy generated for parboiling and drying will require the installation of other engineering process units with their corresponding costs. Table 4 presents the pertinent economic indices for the proposed plant under two import tariff regimes (0 and 5%). It is shown that the simple CHP has the best economic indices, but with a marginal difference over the cascade continuous scenario; for example, the simple CHP LCOE is 5% less than cascade continuous scenario. At 0% import tariff, the simple ORC LCOE is 0.8% less than the 0.123 USD/kWh$_{el}$ of the FGN's Multi-Year Tariff Order (MYTO) for biomass power plant; please, see ref. [59]. However, the simple ORC LCOE is 3.3% more than the biomass power plant MYTO at the 5% operational import tariff. The implication is that the FGN fiscal policy, in the form of import duty exemption for small power production equipment, would increase the economic competitiveness of the proposed plant. The LCOE ranges between 0.12–0.16 USD/kWh$_{el}$ for all the three scenarios under the two import tariff regimes, which is in agreement with 0.12–0.23 USD/kWh$_{el}$ from a similar study by Pode et al. [58] and ~0.12 USD/kWh presented for rice husk ORC plant by Roy et al. [60]. The LCOEs are well below the 0.947[a] USD/kWh estimated for a diesel engine that supplies electrical energy in the cluster of rice mills considered. The breakeven point (BEP) ranges between 7.7–10.7 years under the two import tariff regimes, which compare well with the value of 7.8 years presented by Ofodu et al. [61]. The simple ORC and cascade intermittent scenarios having, respectively, the best and the worst BEP. However, the BEP ranges between 1 – 1.3 years under the LCOE of the diesel engine used in the Abakaliki cluster of rice mills.

Table 4. Economic indices

economic parameter	import tariff %	system configuration		
		simple CHP	cascade continuous	cascade intermittent
LCOE (\$/kWh$_{el}$)	0	0.120	0.126	0.153
	5*	0.125	0.128	0.159
breakeven point (years)	0	7.7	7.9	10.2
	5*	8.0	8.3	10.7
specific investment cost (\$/kW$_{el}$)	0	7065.67	7277.34	7277.34
	5*	7418.95	7641.21	7641.21

***** import tariff for up to 5MW turbine capacity (source: [62])

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[a] Diesel engine based LCOE is based on actual market rate obtained after surveys, which are as: generator cost = 600US\$/kW; replacement cost = 500US\$/kW, fuel cost = 1.10US\$/Litre, maintenance cost = 0.015US\$/hour

3.3 Results of environmental analysis

Fig. 6 presents results for CO_2 reduction potential by substituting RH for fossil fuels (diesel and natural gas) in power generation plants. The results show that a significant reduction of CO_2 emission is assured if RH is substituted for diesel and natural gas in power generation. It is shown that by substituting RH for diesel, 270–483kg of CO_2 emission can be saved from every MWh of energy generated (CHP), which agrees with the more than 400 kg/MWh of CO_2 emissions potential saving reported by Strzalka et al. [19]. It is observed (see Fig. 6) that the emission reduction potential is higher for CHP as against the emission reduction for the case of only power (electrical) generation. This observation could be attributed to the better utilisation of the primary fuel (rice husk in this case) in the CHP as seen from the system efficiency. Furthermore, the emission reduction potential is low for substituting natural gas with the rice husk, which can be attributed to the low emission factor of natural gas fuel. This suggests that a natural gas-fired engine could be an alternative pathway to decarbonise the agroindustry. Even with relatively low electrical efficiency, 180–264 kg of CO_2 can be saved by substituting RH for fossil fuels for every MWh of electrical power generated. It means that an average of about 641 tonnes of carbon per year is saved by substituting the proposed energy system for the diesel engine.

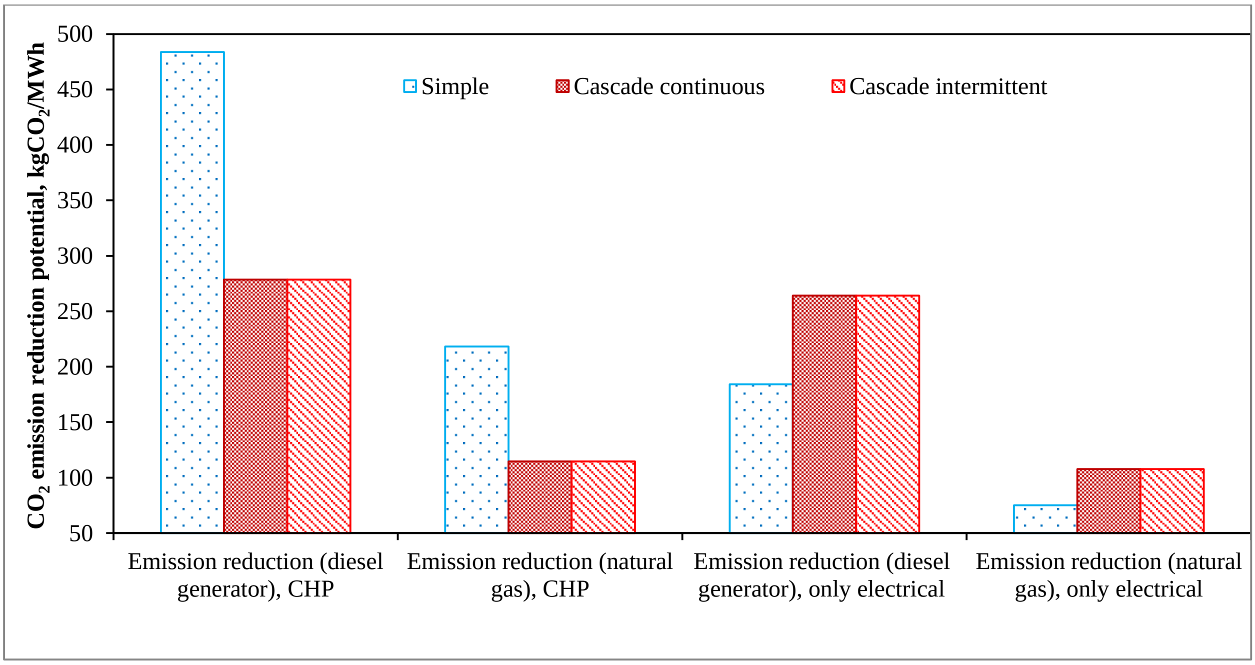

Figure 6 CO_2 emissions reduction potential

It is observed that the three scenarios have different technical, economic and environmental values in the light of providing sustainable electrical and thermal energy for the rice mills cluster. However, the ability of the continuous cascade ORC CHP scenario to provide all-day round electricity, its ability to meet 90.4 % of the peak electrical power demand and the better CO_2 emission reduction potential for electric power generation suggest that the continuous cascade ORC CHP is the choice alternative for sustainable power supply in the cluster of rice mills. It is worthy to note that the 9.6 % peak shortfall could be offset by proper energy efficiency management. However, the simple ORC CHP is appropriate for the thermal energy demand scenario.

3.4 Sensitivity analysis

The rice husk availability, discount rate on capital investment, electricity tariff, import tariff, and cost of the system have been identified to have a strong effect on the techno-economic viability of the proposed system. Therefore, the sensitivity analysis was conducted based on the factors identified.

3.4.1 Rice husk availability

Fig. 7 shows that increasing the RH generation per day increases the energy output of the proposed energy system as expected. The implication is that if the Abakaliki cluster of rice mills is allowed to operate the milling process by additional 2 hours per day (total of six hours) the system is able to generate about 1.65 MW and 2.3 MW of electricity, respectively for the simple and cascade configurations, which are above the cluster's peak electrical power demand. However, the labour cost for the extra two hours may undermine the benefit of the added power. Fig. 7 can be used as a frame of reference for scaling up the proposed energy system to the national level as rice production in the country is growing rapidly, with about 7 million tonnes of rice production (above 1.59 Mtonnes of RH) in 2014[63].

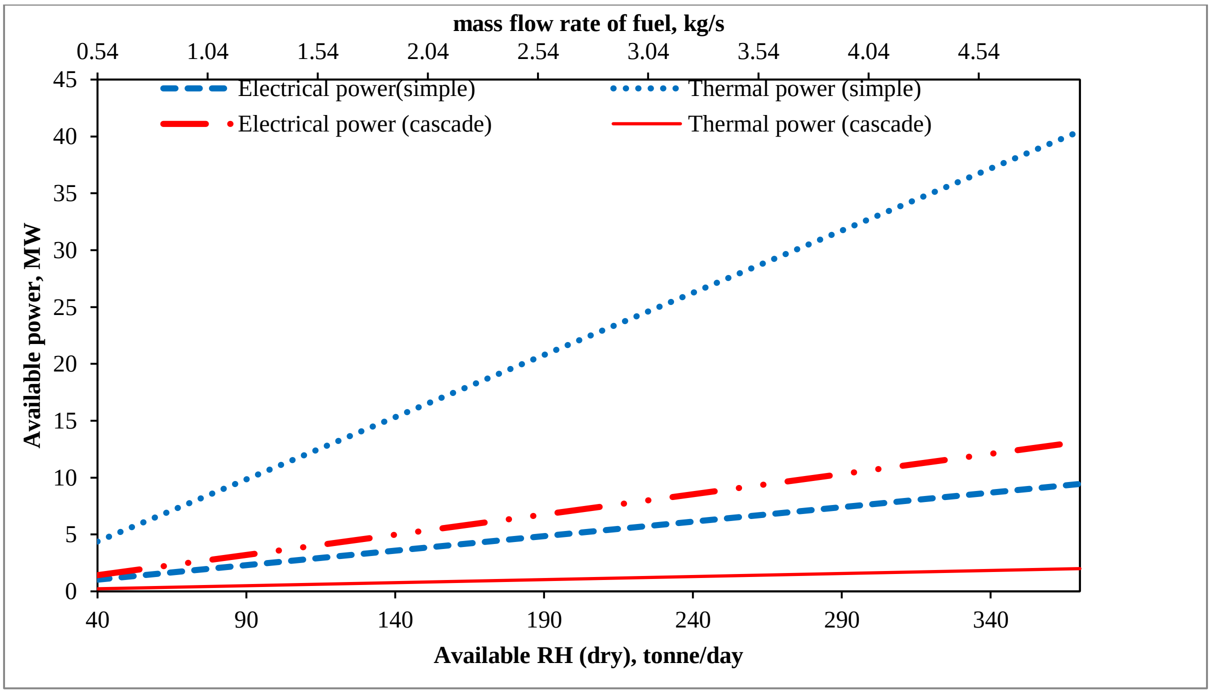

Figure 7 Scalability of power plant

Fig. 8 shows that RH availability has a significant effect on the LCOE. The more abundant the RH is the lesser the LCOE. The implication is that increasing the milling hours by 2 hours per day reduces the LCOE by 8%. This decrease may offset the labour cost for the extra two hours of the milling operation.

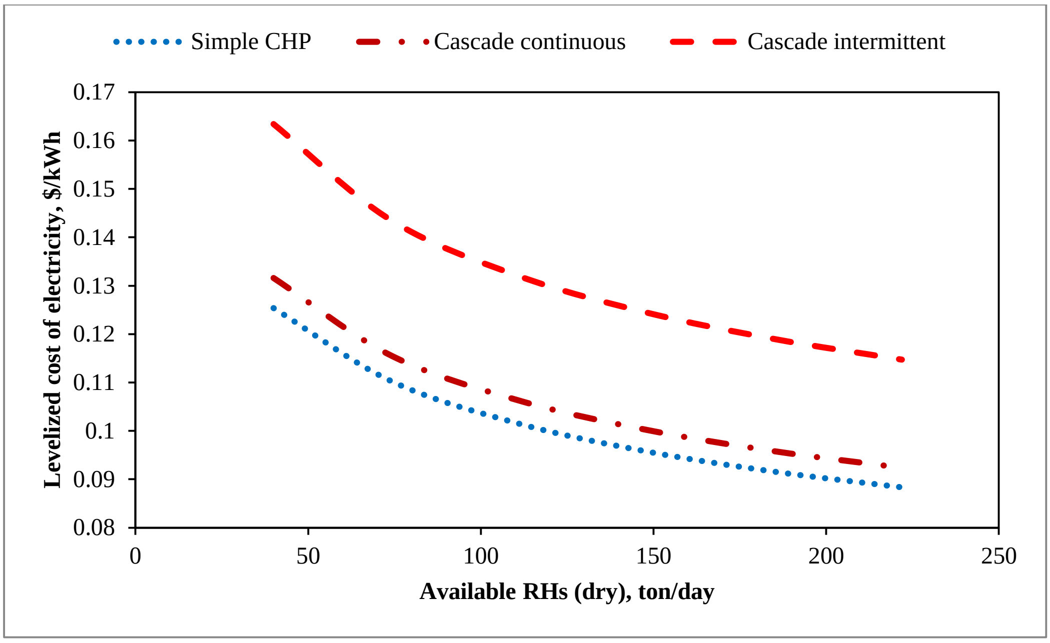

Figure 8 Effect of RH availability on LCOE at 5% import duty

Fig. 9 shows that the specific cost of investment decreases with increasing RH availability. This is expected based on the economy of scale; the higher the system capacity the higher the efficiency and, therefore, improvement in power generated to meet the energy demand, which reduces the specific investment cost. It has been shown that large capacity energy systems have a better fuel efficiency than small capacity thermal systems [64]. The implication is that abundant RH reduces the initial cost of investment, which is an important factor for scaling engineering projects.

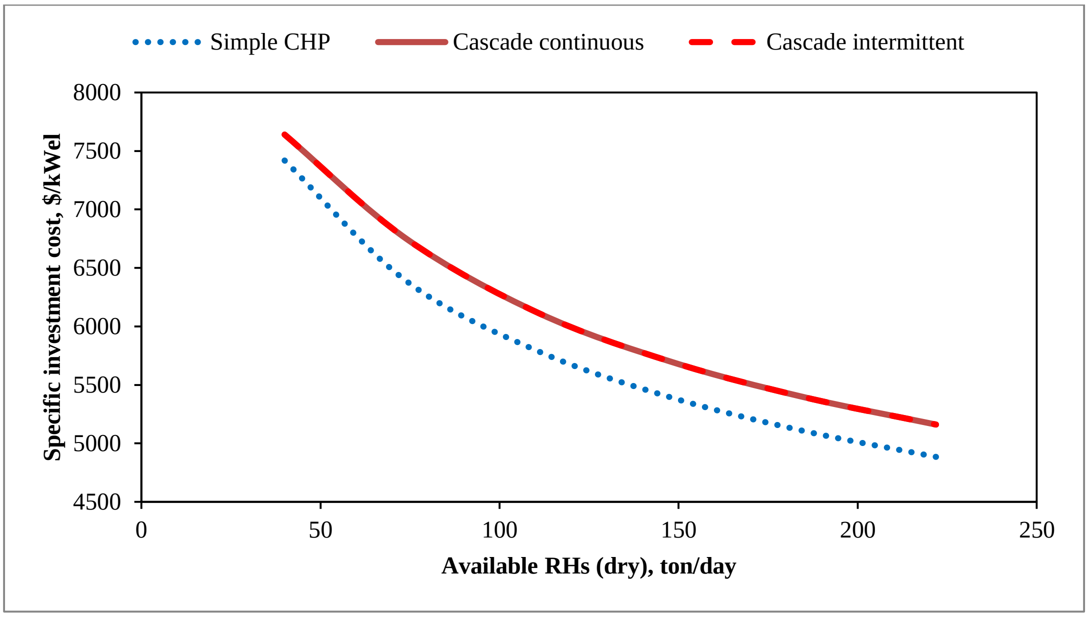

Figure 9 Effect of rice husk availability on specific investment cost at 5% import duty

3.4.2 Discount rate on capital investment

Capital investment cost and unit cost of electricity are sensitive to the change in the discount rate, as presented in Fig. 10. Based on the average value of the discount rate of 9% [57] for the last ten years, the discount rate was varied from 1% to 15% which is within ±25% of the actual average discount value. The discount rate and LCOE have a linear relationship. At a 1% discount rate, which is 45.4% less than the average discount rate, the corresponding average unit cost of electricity of 0.075$/kWh. This unit cost of electricity is 28.75% less than the unit cost of electricity from the national grid. Therefore, FGN positive fiscal policy towards the utilisation of agro-waste in the power sector will complement the economic competitiveness of the proposed system.

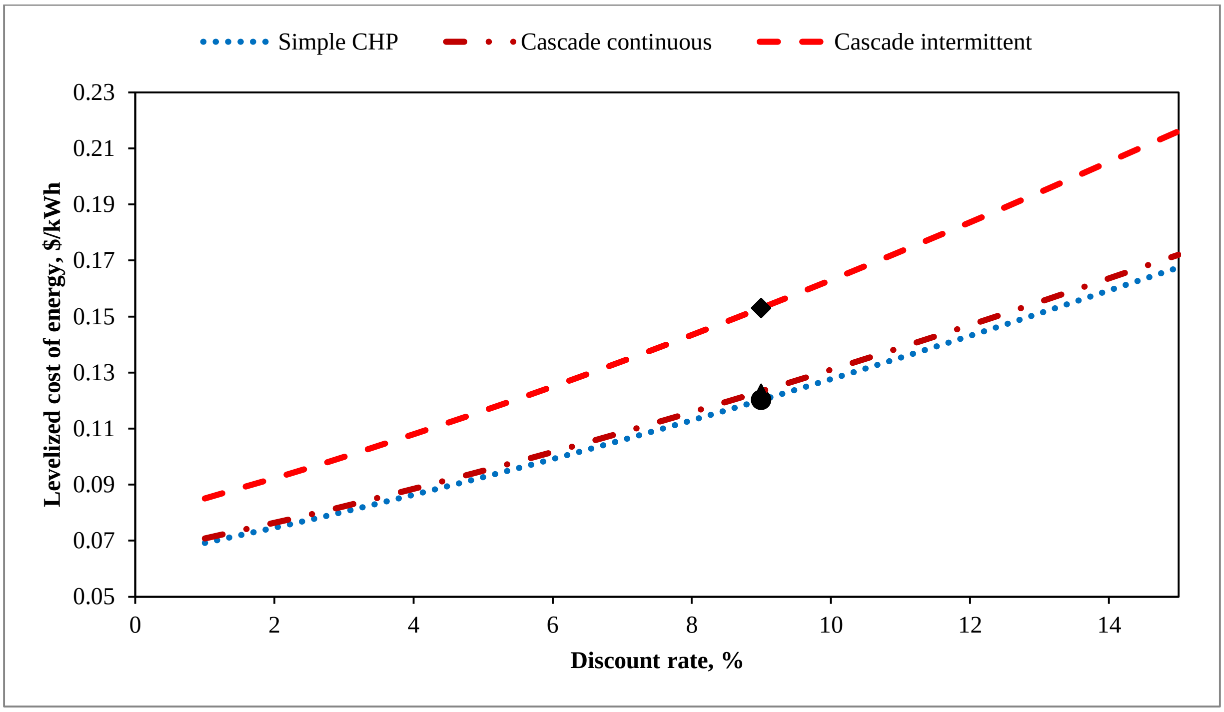

Figure 10 Effect of discount rate on LCOE at 5% import duty

3.4.3 Electricity tariff

The electricity tariff, $/kWh, and the breakeven of the proposed system configurations are presented in Fig. 11. Based on the reference value of the special electricity tariff value of 0.35$/kWh in accordance with the National Renewable Energy and Energy Efficiency Policy, the break-even point of the proposed CHP system is decreased from 8.5 years corresponding to electricity tariff of 0.12 $/kWh to 3.5 years corresponding to electricity tariff value of 0.35$/kWh.

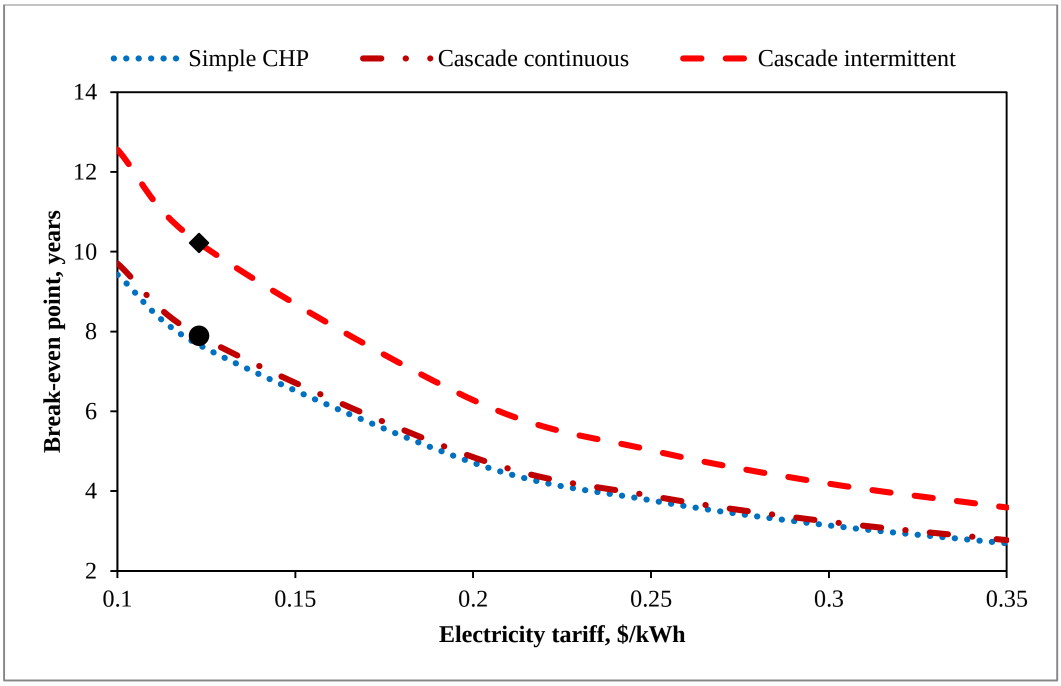

Figure 11 Impact of the electricity tariff on the break-even point of the proposed system

3.4.4 Effects of import tariff

Among other factors, the import tariff has significant effect on the LCOE as presented in Fig. 12. There is linear relationship between the LCOE and import tariff. The LCOE increases with increase in the import tariff which ultimately lead to less economical viable option compared with the price of electricity from the national grid. A decrease of 5% in the import tariff leads to a decrease of LCOE of 3.2%.

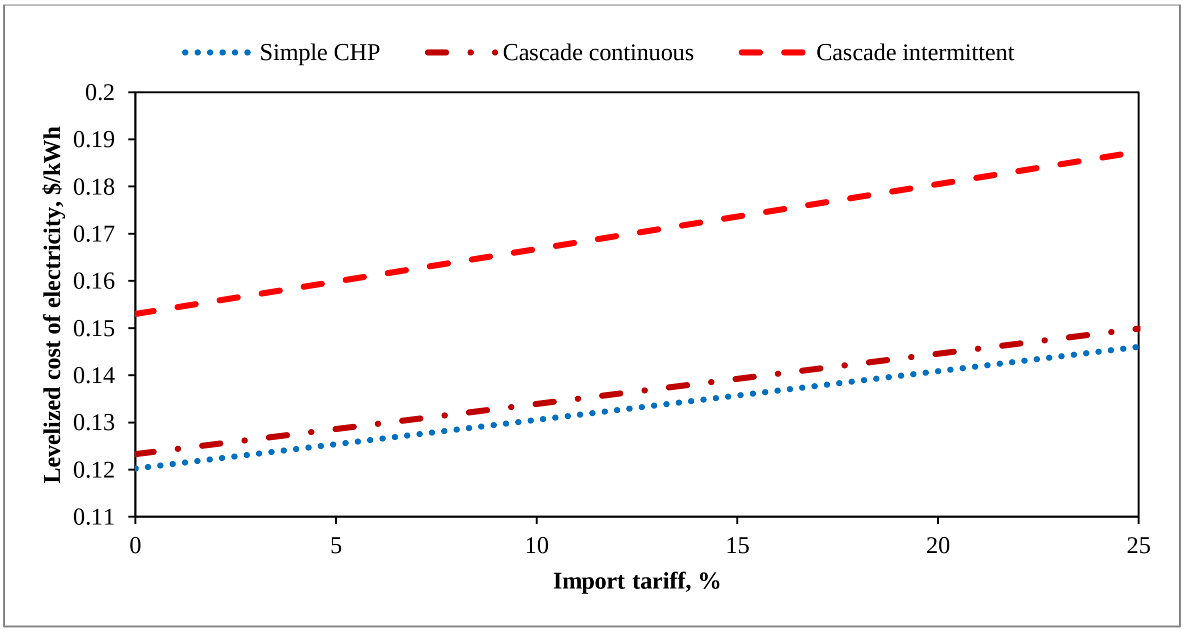

Figure 12 Impact of the import tariff on the LCOE

3.4.5 Effects of the system cost

It is shown in Fig. 13 that reducing the system's cost reduces both the LCOE and the specific investment cost. The implication is that technological advancement, which culminates in cost reduction of technology, will make the system more economically competitive over electricity generation from the conventional power plants that dominate the national grid.

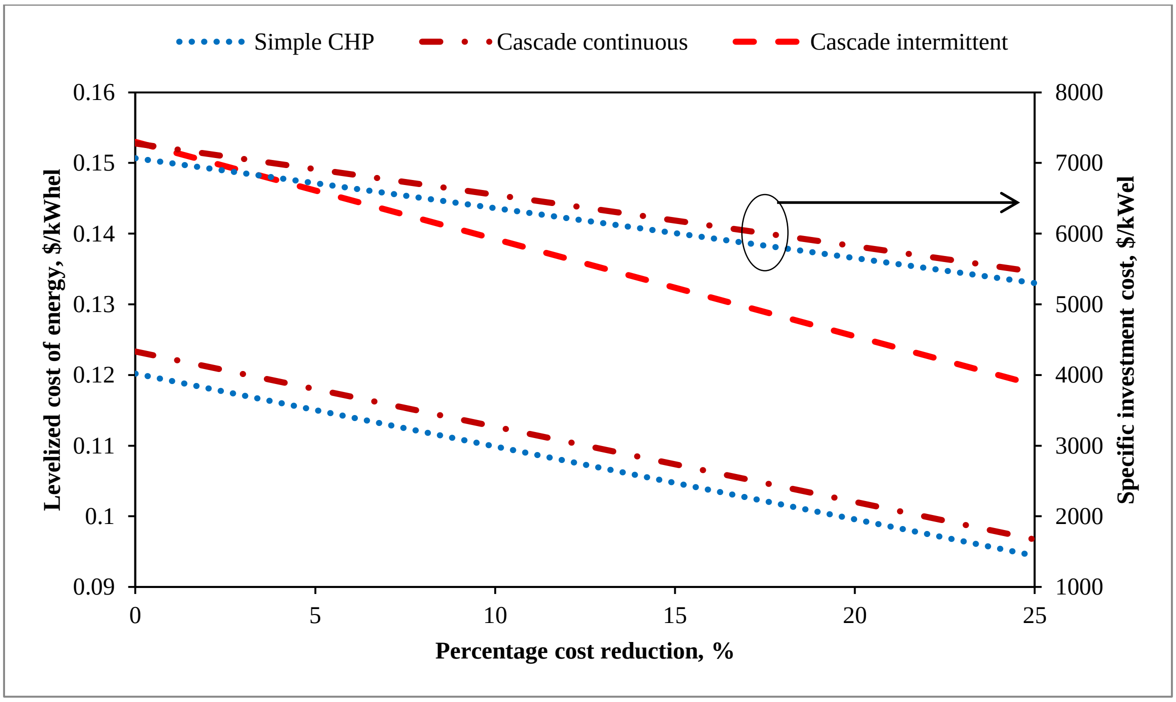

Figure 13 Effects of system's cost on LCOE

4 Sustainable business and energy model

Many businesses and households rely heavily on a diesel engine for power generation in the country, with negative exertion on the environment – emissions and noise. Besides, the cost of electricity from diesel generators is relatively expensive (above 0.90 $/kWh); thereby, making local products (e.g. rice) to be expensive than foreign counterparts. Therefore, the proposed business and energy model (as shown in Fig. 14) is fashioned in a manner to improve the economic competitiveness of agro-industries and nearby cottage industries and households. The business and energy model are integrated in such a way that it does not only meet the energy demand but also tends to improve the economic competitiveness of agro-industries and local communities, as shown in Fig. 14. It has been demonstrated that the RH-fired CHP ORC plant represents a very interesting solution for small power production as a business venture since RH fuel is immune from external threat and readily available[58]. The model ensures that the rice processing is energy self-sustained.

In the proposed sustainable business and energy model, the cluster of rice mills generates power (electrical and thermal) to sustain its own energy demands and that of nearby businesses and households. It is possible for the cluster to meet all its energy demand and sells the balance to the neighbourhood. The rice mill owners have the opportunity to bring in revenue from two sources – revenue from selling processed rice and energy. In addition, the RH ash from the post-combustion process could be turned into useful economic by-products, namely fertilizer, ceramics, cement-based materials [42]etc. This is very important as it will serve as a channel to also mitigate the environmental impact of heavy-laden silica ash (with silica > 85%[65]) associated with the rice husks post-combustion. In this approach, cement-based materials could easily be manufactured to support sustainable buildings. However, the rice mill owners will invest in both the mill machinery and the power generation plant. Electrical energy is the most desired energy; therefore, the focus of energy pricing is based on the electrical energy that can be generated. The electrical energy pricing should be based on household income (mainly in the rural dwellings) and business profitability. For example, the pricing could be 0.35USD/kWh for the first three years, which correspond to the break-even point for the cluster of rice mills considered; and, thereafter, progressively reduce the cost per energy to match the cost per electrical energy supplied by the national grid.

The model envisages harmony among the rice mill owners, the local community and the local cottage industries, especially ceramic and cement-based material industries in the context of utilisation of the ash from the rice husk post-combustion. There shall be an established Local Energy Committee (LEC), which will interface between the rice mill owners and the local communities. The LEC buys bulk electrical energy from the rice mill owners, whereas the rice mill owners maintain the distribution networks to ensure a continuous supply of electrical energy. The LEC sells the electrical energy to the local cottage industries and households through a monthly prepaid fee model depending on the energy affordability index accordingly established.

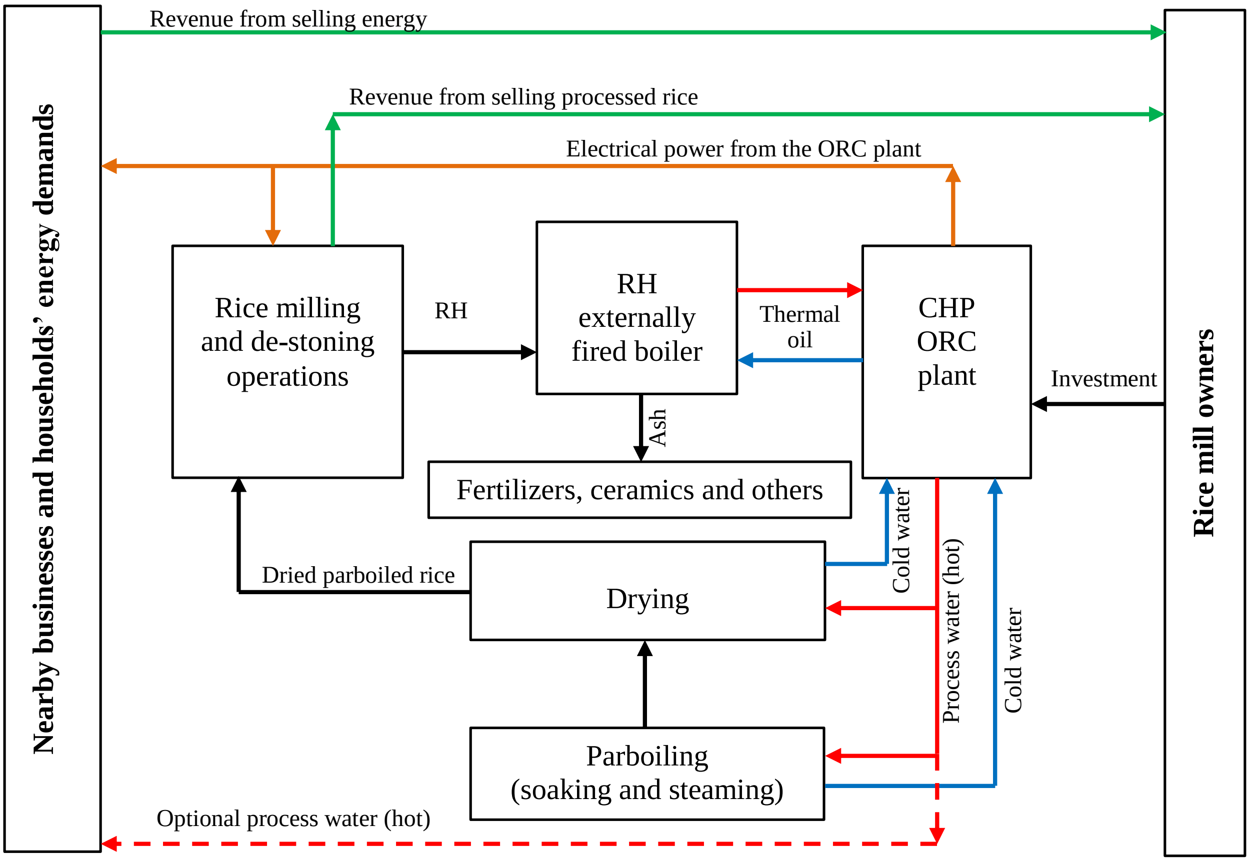

Figure 14 Sustainable business and energy model

5 Conclusion

The work presents three scenarios of sustainable energy supply in a cluster of rice processing mills, located in Abakaliki, Nigeria, based on the circular economy – the rice husks waste generated are used as fuel. It is shown that the cluster of the rice mills has the potential to meet its energy needs, including the local community, through the utilization of rice husk in an organic Rankine cycle based combined heat and power (CHP) cycle power plant. The three scenarios of the combined cycle power plant, namely simple combined cycle power plant, cascade combined cycle power plant continuous, and cascade combined cycle power plant intermittent, were investigated for complete information. The results of the current analysis could be summarised as:

- That the available rice husk resource has the potential of providing 20–30MWh and 4–91MWh per day of electrical power and thermal power, respectively, even at a relatively low efficiency between 14.5–21%.
- That about 0.45–0.65 MWh of electricity per tonne of rice husk can be generated by the rice husk fired combined power and heat organic Rankine cycle power plant.
- That the peak electrical demand of the rice mills cluster (about 1.61MW) cannot be met except through aggressive adoption of energy efficiency measures to reduce electrical energy demand by at least 9.6%.

- That the unit cost of electricity from the proposed system ranges between 0.12–0.159$/kWh, which is more competitive than 0.947 US$/kWh for the diesel generator currently in use at the mills cluster.
- That about 270–483 kg of CO_2 emission can be saved from every MWh of energy generated by substituting the proposed combined cycle power plant for the diesel engine.

Going forward, the work presents a novel business model for the utilisation of the proposed energy system in the cluster of rice mills. The business model suggests a coupling between agroindustry and sustainable building development in the context of environmental management and circular economy. In the context of climate change mitigation and environmental sustainability, the adoption of the proposed CHP energy system fired by agro-wastes across the value chain of agroindustry in Nigeria has the potential of significantly decarbonising the agroindustry for its competitiveness and potential to support the country to meet its commitments to the Paris Agreement as enshrined in its Nationally Determined Contributions. It, therefore, beckons on the government to initiate agroindustry policies that will aggressively drive the adoption of the proposed CHP in the entire agriculture sector. However, the socio-economic and political economy of livehood surrounding the implementation of clean energy access would need to be fundamentally addressed from the policy dimension in future work.

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