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Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant

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ABSTRACT

This paper presents the energy, exergy, environmental and economic analysis of a proposed agricultural waste-to-energy integrated multi-generation power plant. The proposed plant will use agro-wastes composed of selected crops and animals wastes from a farm in Rivers state, Nigeria (latitude 4.44°N, longitude 7.1°E). Combined anaerobic digestion and gasification was used in converting the agro-wastes to synthetic gas, and subsequently converted to electrical energy and refrigeration in an integrated multi-generation plant composed of solid oxide fuel cell stack, gas turbine, steam turbine, organic Rankine and absorption refrigeration cycles. The lower heating value of the syngas is estimated as 23.47 MJ/kg; the proposed plant had a net power of 5.226 MW, energy and exergy efficiencies of 63.62 and 58.46%, respectively. The highest exergy destruction rate was in the combustion chamber with a contribution of 15% to the overall exergy destructed. Life cycle cost of $3.753 million, breakeven point of 7.5 years and unit energy cost of $0.0109 per kWh were obtained. Environmental analysis showed specific emission of CO_2 of 141.2 kg/MWh and sustainability exponent of 3.65, with exit flue gas stack temperature of 60.4 °C, respectively. The paper introduced energo-environmental sustainability and energo-economic sustainability exponents to holistically assess the sustainability of the proposed plants.

1. Introduction

Sustainable, clean and affordable power supply is key to the success of any organization whose goal is to impact positively on the society and the environment by reducing pollution from fossil fuel resources, utilizing readily available and cheap renewable resources from agricultural waste [16,37]. According to Charles [13], a stable power generation and supply from agricultural waste is possible in Nigeria. With appropriate technology and policies, clean and sufficient power can be made available to meet the energy challenges of the Nigeria [33].

Papapostolou et al. [39] showed that waste-to-energy generation schemes are an attractive option, producing energy with low pollutant emissions, low cost and elimination of waste accumulation. Also exploiting biomass from agricultural residues (livestock manure and crop wastes) exhibits beneficial features as there is no interference with the production of primary food and is available at low cost. Biomass can be converted into energy through gasification and anaerobic digestion to syngas (which comprises hydrogen, carbon dioxide and methane) and biogas (methane) that can be used as fuel in power plants [6]. Gasification is a thermo-chemical process whereas anaerobic digestion is a bio-chemical process; both of which are the most likely cost effective conversion processes of biomass. Solomie et al. [47] performed an economic analysis of anaerobic digestion of a biogas plant situated in a farm using net present value (NPV) and internal rates of return (IRR) concepts; they concluded that the conversion process is economically viable. Hailong et al. [20] investigated the technology that combines anaerobic digestion and biomass gasification to produce bio-methane with the hydrogen gas from the syngas used in upgrading the biogas from anaerobic digestion. Shahida and Mohd [44] analysed the potential of power generation from biogas obtained from palm oil waste (palm oil mill effluent). They confirmed its technical and economic viability, citing possible investment sizes of such biogas production plant. Rade and Zoran [41] considered piggery wastes for generating biogas fuel for a cogeneration plant of 3 MW. Equilibrium models to predict the amount of gasification product in a downdraft gasifier have been developed by Zainal et al. [52], Jarungthammachote and Dutta [23], Athari et al. [4] and Allesina et al. [2]. Predicted values from their results compared reasonably with experimental data for different biomass. Spyridon and Gerrit [48] developed a theoretical model of anaerobic digestion in order to predict the amount of biogas in animal waste slurries.

According to Dincer and Ratlamwala [17], the concept of multi generation system is aimed at recovering thermal energy in waste heat

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Nomenclature

h	specific enthalpy, kJ/kg
P	pressure, kPa
$\bar{R}$	gas constant, kJ/kmol K
c_p	isobaric specific heat capacity, kJ/kg K
$\dot{Q}$	heat, kW
X	concentration of LiBr
$\dot{z}$	molar flow rate of fuel, kmol/s
f	fuel
st	steam
s	specific entropy, kJ/kg K
T	temperature, °C or K
$\dot{m}$	mass flow rate, kg/s
$\dot{W}$	power, kW
η	efficiency
n	number of moles, kmol
a	air
g	flue gases

Abbreviations

ABS	absorber
AC	air compressor
ARCOND	absorption refrigeration condenser
CC	combustion chamber
EVP	evaporator
EX	expansion valve
FC	fuel compressor
GEN	absorption refrigeration generator
HP-HRSG	high pressure heat recovery steam generator
HP-ST	high pressure steam turbine
HROVG	heat recovery organic vapour generator
HX	preheater
INV	inverter
LP-HRSG	low pressure heat recovery steam generator
LP-ST	low pressure steam turbine
MT	micro turbine
OFCOND	organic fluid condenser
P	feed water pump
PP	preprocessor
POME	palm oil mill effluent
SOFC	solid oxide fuel cell
SReg	solution regenerator

in order to improve the efficiency and economy of the system. Solid oxide fuel cell (SOFC) has been used for power generation, in hybrid systems, combined heat and power generation and for combined cooling, heating and power generation; with operating temperature of 500 (°C) to 1000 (°C) and power of 2 kW to several megawatts [7]. SOFC also produce significant quantity of waste heat due to its high operating temperature, and off-fuel, making it possible for it to be coupled with a gas turbine or an organic Rankine cycle (ORC) or a steam turbine as a bottoming cycle for total efficiency improvement [31]. Siefert and Litster [43] presented an exergy and economic analysis of an integrated biogas plant with an SOFC and gas turbine (GT) power unit. Their results showed the economic viability of an SOFC-GT power plant fueled by biogas. Harfei [21] and Ebrahimi and Moradpoor [18] considered an SOFC, micro-gas turbine and ORC for power generation. Their results show that an increase in thermal efficiency is achievable in micro-scale power generation. Sreeramulu and Deepak [49] carried out a comparative analysis of an SOFC-GT combined power cycle fueled with natural gas and diesel, respectively. High exergy destruction was recorded in the SOFC and combustion chamber of the plant. Fahad et al. [19] studied the energy performance of a tri-generation plant with an SOFC, ORC, a heat exchanger for process heat and a single effect absorption refrigeration system (ARS) for cooling. Their result show 22% gain in efficiency with trigeneration when compared with only the SOFC and ORC only. The use of trigeneration systems ensures higher exergy efficiency and lower emissions [1,14,32].

Bellomare and Rokni [9] considered an integrated gasification SOFC-GT plant fueled with syngas produced from the gasification of biomass. An optimum efficiency of 52% was obtained. Pirkandi et al. [40] carried out a performance analysis of a SOFC combined heat and power plant and obtained an overall efficiency of 73%. The thermo-economic analysis of four different configurations of natural gas and biogas fed SOFC was carried out by Mehr et al. [29]. Their results showed a maximum thermal efficiency at current density of 6000 A/m^2, with an optimum anode recycling ratio of 0.25–0.3. Thermal efficiency of the biogas fed SOFC was higher than that of natural gas. Haseli et al. [22] examined the performance of high temperature SOFC combined with an air preheater and a dual-pressure gas turbine. Their results indicated that an increase in the turbine inlet temperature resulted in the decrease of the thermal efficiency of the cycle and increased net power output. Also the combustion chamber and the SOFC had the highest irreversibilities of 31.4 and 27.9%, respectively. Maximum thermal efficiency of 60.6% was obtained at a compression ratio of 4.0. Chan et al. [11] presented a hybrid SOFC-GT power plant with internal reforming, fueled by biogas. They obtained an energy efficiency of 60%, and also showed that high operating pressure improves the systems efficiency, while increase in specific fuel consumption decreases the plant output.

Absorption refrigeration systems (ARS) utilize low grade, low cost thermal energy available to produce cooling. In commercial systems, two commonly used refrigerant-absorbent pairs are Water-Lithium Bromide (LiBr-H_2O) and Ammonia-Water (NH_3-H_2O). LiBr-H_2O, with water as the refrigerant and lithium bromide as the absorbent, is suitable for moderate temperature applications (above 5 °C), such as air conditioning·NH_3-H_2O is for low temperature applications (below 5 °C) with ammonia as the refrigerant and water as absorbent[17]. Shahata et al. [45] and Al-Tahaineh et al. [3] studied vapour absorption refrigeration using the First and Second law of thermodynamics, with results that showed maximum coefficient of performance (COP) and exergetic efficiency at low values of absorber and generator temperatures. Bhargav et al. [10] and Zadeh and Narvid [53] analysed a single effect absorption chiller for air conditioning purpose, with LiBr-H_2O as the working fluid. From their results, high exergy loss was recorded in the generator of the system.

According to Oyedepo et al. [38] and Memon et al. [30] reduced flue gas temperature reduces the fuel harmful emissions to the environment and is beneficial in increasing the system efficiency, thereby increasing the sustainability of the plant with regards to fuel resources. Saidur et al. [42] identified a reverse relation between a power plant's sustainability index and environmental impact with respect to exergy efficiency, as sustainability increases the environmental impact decreases with increased efficiency.

While many studies have been devoted to the study of multi-generation power plants, study on combined anaerobic digestion and gasification to convert agricultural wastes to electrical energy and refrigeration in an integrated multi-generation plant comprised of solid oxide fuel cell stack, gas turbine, steam turbine, organic Rankine and absorption refrigeration cycles has not been fully established in terms of energy, exergy, environmental and socio-economic analyses. Furthermore, study on holistic sustainability (combined energo-economic, energo-environment and energo-social sustainability exponents)