Integrated Power Plant Fired by Syngas from Solid Wastes and Natural Gas with Case for Energy Storage

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Abstract. The study presents an integrated power generation system fired by dual-fuel (syngas from solid wastes and natural gas) with a carbon capture technology to minimize greenhouse gas emissions from power plants and landfills. This study is vital because the upstream power sector's decarbonisation is necessary for attaining a low emission future. The study results show that electrical power at 208.8 MW can be harnessed from an optimal syngas and natural gas composition at 0.47 and 0.53, respectively. The technical efficiency of the system is 43%; the carbon dioxide (CO2) emission factor is 0.029 tonnes per MWh, and the CO2 transportation rate is 612.2 kilotonnes per year. The total cost of the proposed power system is estimated at USD 236.7 million, the unit cost of energy is 0.141 USD per kWh, CO2 avoidance cost is 110 USD per tonnes of CO2, and the payback period is 5.2 years. The study also presents a pathway to incorporate hydrogen energy storage into the proposed plant for the reliability of electricity supply at all seasons. However, future research work is required to optimally incorporate hydrogen energy storage into the proposed integrated power plant.

Keywords: Dual fuel · syngas · carbon capture · clean energy access · integrated power plant · climate change · decarbonisation · hydrogen energy storage

1 Introduction

In view of the Sustainable Development Goals and Paris Agreement, clean energy is fast becoming a fundamental need that must be met in this decade. Poorly electrified economies are in search of sustainable ways to meet their growing electricity needs, as most of the future electricity shortfall, estimated as 90%, will come from these economies [1]. Also, most of the energy supply of the developing, poorly electrified, and oil and gas-rich countries are heavily dependent on fossil energy sources, which are depleting and major contributors to climate change. Utilizing dual fuel (syngas and natural gas) in power generation systems with carbon capture can significantly improve energy access

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and climate. Dual-fuel power generation systems benefit from low carbon emissions and high fuel heating value [2].

Integrated power generation systems are very common, and they are power systems that combine two or more power generation technologies. Integrated power systems may also extend to co-generation (combined heat and power) and tri-generation (combined heat, power and cooling). It is widely accepted that an integrated power system is a better way to properly harness the primary energy - it provides more power at the same energy input as a simple cycle power plant; it contributes to reduced environmental impact in both thermal and emission terms; and increases system efficiency [3–5].

Apart from electricity generation, energy storage is pivotal in maintaining a stable and reliable electricity system. The intermittency of most renewable energies and off-peak hours of energy demand requires that energy be stored during excess production and used during peak hours and periods of low generation. Several techniques have been widely reported, including thermal, mechanical, electrical, electrochemical, and chemical [6]. The IPCC has reported that hydrogen storage has gained the centre stage of discussion as a vital energy carrier that can significantly drive the 1.5 °C energy transition [7]. In hydrogen storage, excess electricity is converted to hydrogen by electrolysis, a process that is tagged ‘green hydrogen’. The produced hydrogen can react with oxygen in a fuel cell to generate electricity during periods of high electricity demands. Different modes have been identified for hydrogen storage, including compression, liquefaction, metal hydrides, etc.

Nigeria is strategically positioned to benefit from numerous energy sources to meet all its current and future energy needs [8]. However, the country’s overdependence on oil and gas is partly attributed to the country’s poor electrification. In addition, the electricity from oil and gas-fired power plants pollutes the environment and contributes to the global warming induced by greenhouse gases. The first Nigeria Nationally Determined Contribution (NDC) sees the power sector as a single sector that could contribute one-third of the greenhouse gas reduction in Nigeria by 2030. Whereas the revised NDC suggests that electrification of other sectors is key to attaining a low carbon economy [9, 10]. However, the country lacks evidence to support clean electricity development strategies and policies. It is against this background that the present work is carried out. Therefore, this study investigates an integrated power generation system (with future energy storage) to improve energy access in Nigeria and decarbonize power generation. This study is novel in that the thermal power generation plants in Nigeria are majorly simple cycle power plants; and in addition, the country’s thermal power plants have no carbon mitigation fixtures. Furthermore, the study presents strategies to avert future capacity shortage through the incorporation of energy storage.

2 Methodology

An integrated power plant is proposed in this study. This plant comprises of solid oxide fuel cell, gas turbine, steam turbine, organic Rankine cycle (ORC), absorption refrigeration and carbon capture technologies. The plant configuration is shown in Fig. 1. The proposed system is fired by dual fuel (syngas and natural gas). The syngas, a product of the gasification of municipal solid waste generation in the city of Port Harcourt, is presented in detail in ref. [3]. In Fig. 1, the SOFC-GTC, ST cycle and ORC cycle are different power generation units of the proposed configuration; the AR cycle is an air cooling cycle that is used to improve the power generation of the gas turbine cycle and also to cool the various condensers of the system; while the CCC unit is the carbon capture cycle used to decarbonize the power generation process. The system is modelled in respect of technical, economic and environmental. The basic technical equations applied in this study are energy and exergy balances. See Table 1 for the summary of the energy and exergy equations of each of the components of the power plant configuration and [4, 11] for details of the modelling.

The life cycle cost of the plant sums the cost of primary energy, equipment costs, and operation and maintenance cost (O&M). This is shown in Eq. (1), while the unit cost of electricity is shown in Eq. (2). Again, see ref. [11] for details of the equipment

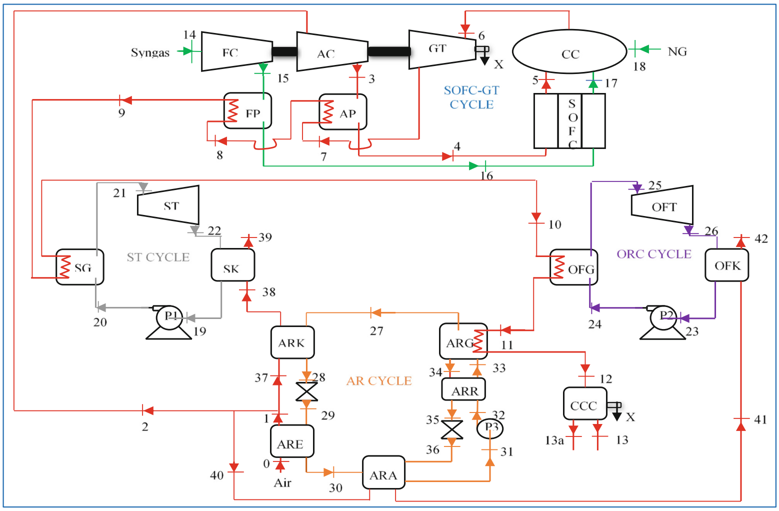

Fig. 1. Proposed integrated power system

Table 1. Thermodynamics equations of various components of the system

Components	Energy	Exergy balance
Compressor	$\dot{W}_c = \dot{m}_a c_p (T_j - T_i)$	$\dot{E}x_i + \dot{W}_c = \dot{E}x_i + \dot{E}x_{d,c}$
Heat Exchanger	$\dot{Q}_k = \dot{m}_k c_p (T_j - T_i)$	$\dot{E}x_i + \left(1 - \left(\frac{T_0}{T_k}\right)\right) \dot{Q}_k = \dot{E}x_j + \dot{E}x_{d,hx}$
Turbine	$\dot{W}_t = \dot{m}_k c_p (T_i - T_j)$	$\dot{E}x_i = \dot{E}x_j + \dot{W}_t + \dot{E}x_{d,t}$
SOFC	$\dot{W}_{SOFC} = IV$	$\sum_i \dot{E}x_i = \sum_j \dot{E}x_j + \dot{W}_{SOFC} + \dot{E}x_d$
Combustor	$\dot{Q}_{cc} = \dot{m}_f LHV$	$\dot{E}x_i + \dot{E}x_f = \dot{E}x_j + \dot{E}x_{d,cc}$
Pump	$\dot{W}_p = \frac{\dot{m}_w v (P_b - P_k)}{\eta_p}$	$\dot{E}x_j + \dot{W}_{P1} = \dot{E}x_i + \dot{E}x_{d,p}$
Absorber	$\dot{Q}_{ARA} = \dot{m}_r h_r + \dot{m}_{ws} h_{ws} - \dot{m}_{ss} h_{ss}$	$\dot{E}x_{r,i} + \dot{E}x_{ws,i} + \dot{E}x_{i'} = \left(\dot{E}x_{ss,j} + \dot{E}x_{j'}\right) + \dot{E}x_{d,Abs}$
Regenerator	$\Delta \dot{H}_{ARR} = \dot{m}_{ws} \left(h_{ws,i} - h_{ws,j}\right)$	$\dot{E}x_{ws,i} + \dot{E}x_{ss,i} = \left(\dot{E}x_{ws,j} + \dot{E}x_{ss,j}\right) + \dot{E}x_{d,Reg}$
Throttling valve	$\dot{m}_{ws} h_{ws,i} = \dot{m}_{ws} h_{ws,j}$	$\dot{E}x_{ws,i} = \dot{E}x_{ws,j} + \dot{E}x_{d,TV}$
Solution generator	$\dot{Q}_{ARG} = \dot{m}_g c_{pg} (T_i - T_j)$	$\dot{E}x_i + \dot{E}x_{ss,i} = \left(\dot{E}x_j + \dot{E}x_{r,j} + \dot{E}x_{ws,j}\right) + \dot{E}x_{d,Sol}$

costs of the various components of the system.

$$Z_{LCC} = \sum_{q} Z_q;\ q \in \{SOFC, GTCC, STC, ORC, ARC, CCS, O\&M\} \quad (1)$$

$$UCOE = \frac{Z_{ALCC}}{365 \times E_{DP}} \quad (2)$$

where, $Z_{ALCC}(\$/yr)$ and $E_{DP}(kWh/d)$ are the annualized life cycle cost and daily energy production, respectively.

The unit cost of CO_2 avoidance is shown in Eq. (3).

$$c_{CO2,Avoid} = \frac{UCOE_{CCS} - UCOE_{ref}}{SE_{CO2}^{ref} - SE_{CO2}^{CCS}} \quad (3)$$

where, SE_{CO2}^{CCS} and SE_{CO2}^{ref} (kg/kWh) are the CO_2 emissions per unit energy production for the power plants with carbon capture and without carbon capture, respectively.

The climatic impact of the power generation system is described in terms of the amount of CO_2 produced and the specific emission of the plant. These are presented in Eqs. (4) and (5), respectively.

$$\dot{m}_{CO2} = y_{CO2}\dot{m}_g\left(\frac{\overline{M}_{CO2}}{\overline{M}_g}\right) \quad (4)$$

$$SE_{CO2}^{CCS} = 3600\left(\frac{\dot{m}_{COO2}}{\dot{W}_{net}}\right) \quad (5)$$

3 Results and Discussion

The thermodynamic performance of the plant is shown in Table 2. The results proposed a net power of 208.8 MW from 47 and 53% syngas and natural gas compositions, respectively. This is at an efficiency of 42.9%. The relatively low efficiency is due to the energy requirements for the carbon capture process. At 208.8 MW of power generation, the electricity needs of 988 or 2540 thousand households in Nigeria can be met by the per capita electricity consumption in Sub-Saharan Africa or Nigeria, respectively. In Table 2, the CO_2 emission factor is proposed as 0.029 tonnes per MWh, when compared to conventional thermal power plants with an emission factor of 0.4 tonnes per MWh [2]. Nonetheless, this low emission factor is at the expense of the net power generation. Furthermore, the CO_2 capture from the flue gases put at 612.2 ktonnes per annum has the potential for oil recovery in depleted oil and gas reservoirs.

Table 3 presents the economic merits of the power plant. This includes the total cost of the plant, unit cost of energy, cost of CO_2 avoidance, and the payback period at $ 236.7 million, $ 0.141 per kWh, $ 110 per tonne and 5.2 years, respectively. The value of the unit cost of energy has shown that the proposed plant will thrive comparably with most of the power generation systems that are prevalent in Nigeria. For instance, the cost of running petrol and diesel generators are within $ 0.3–0.6 per kWh, while the cost of

Table 2. Thermodynamics performance of the power generation plant

Plant	Parameter	Units	Values
SOFC	Power	MW	54.68
GTC	Power	MW	102.2
STC	Power	MW	39.03
ORC	Power	MW	12.93
ARC	Refrigeration capacity	MW	39.2
CCS	CO_2 capture	%	93.5
SOFC-GT-ST-OR-AR-CCS	Power	MW	208.8
	Energy efficiency	%	42.93
	Exergy efficiency	%	42.49
	Total exergy destruction	MW	322.9
	CO_2 emission factor	tonnes/MWh	0.029
	CO_2 transported	ktonnes/y	612.2
	CO_2 emissions	ktonnes/y	42.56

Table 3. Economic quantification of power plant

Parameter	Units	Values
Total cost of power plant	Million $	236.7
Unit cost of energy	$/kWh	0.141
Cost of CO_2 avoidance	$/tonne	110
Payback period	Years	5.2

municipal electricity is $ 0.13 kWh [12]. The relatively high cost of the plant as against the cost of municipal electricity may be justified by 94% of the flue gases' CO_2 that is captured from the plant. This becomes significant when the social cost of CO_2 emissions of $ 220 per tonne of CO_2 [13] is put in view.

3.1 Case for Energy Storage

A background study suggests that the waste availability is seasonal, with high waste generation in the dry season. In addition, the waste generated during the rainy season would not be able to fire the proposed integrated power plant at full capacity in the perspective of high cost and the long period of waste treatment during the rainy season. Furthermore, for localized municipal power generation, the electricity from the high volume of waste during the dry season would surpass the electricity demand in the Port Harcourt metropolis. Moreover, the current trend of energy generation favours distributed energy generation. Therefore, energy storage must be considered to address the potential

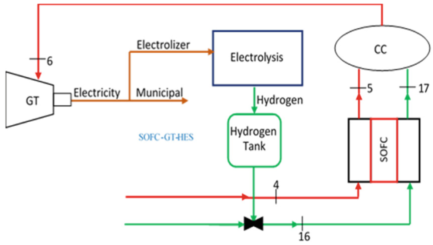

Fig. 2. Process diagram to incorporate the energy storage

capacity shortage in the rainy season. The IPCC has reported that hydrogen storage has gained the centre stage of discussion as a vital energy carrier that can significantly drive the 1.5 °C energy transition [7]. In this regard, this work suggests the integration of hydrogen energy storage (HEN) into the proposed integrated power system for improved reliability. The energy storage is considered in the proposed integrated power plant by retrofitting it with Fig. 2 by modifying the SOFC-GT Cycle in Fig. 1 to SOFC-GT-HES. The hydrogen energy storage is achieved through water electrolysis during periods of high electricity generation or low energy demands. After this, the stored hydrogen is used during periods of high energy demands or low gas supply/waste stream generation. The stored hydrogen is converted back into electricity via the proposed study's fuel cell process (SOFC) subsystem. However, detailed thermodynamics and economic analyses are required to optimally match the hydrogen energy storage with the proposed system. Therefore, future research work would focus on the 4Es (energy, exergy, environment and economic) analysis of the proposed integrated power plant with energy storage.

4 Conclusions

The developing countries with large oil and gas reserves are faced with a combined burden of lack of energy access and the efforts to decarbonize the energy sector to meet the Paris Agreement and Sustainable Development Goals. About 40% of Nigeria's population has no access to electricity. Energy access is poor, and the few gigawatts (about 13 GW) of electricity installed in the country is majorly fossil fuel without any means for mitigating CO_2 emission from the power plants. This work conducted a techno-economic analysis of a decarbonized integrated power plant fired by syngas from municipal solid waste and natural gas and suggested hydrogen energy storage for enhanced reliability of generation and supply. The power plant units included the SOFC, gas turbine, steam turbine, ORC, absorption refrigeration cycle, and carbon capture technology with a case for energy storage. The work provides promising environmental and economic results. Again, the results suggest that almost 94% of the CO_2 generated can be captured, and 612.2 ktonnes are transported to depleted oil and gas reservoirs for enhanced oil recovery. At 94% carbon capture, the emission factor of the plant is only 0.029 tonnes per MWh as against 0.4 tonnes per MWh in conventional power plants. The unit cost of energy is between $ 0.141 per kWh, which is cheaper than the cost of running petrol and diesel generators in Nigeria, at $ 0.3–0.6 per kWh. The study also presented a pathway to incorporate hydrogen energy storage into the proposed integrated power plant to improve the reliability of power generation. Going forward, future research work will be dedicated to the 4Es (energy, exergy, environment and economic) analysis of the proposed integrated power plant with energy storage.

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Authors' Contributions. The authors contributed equally.

References

1. IEA, "World Energy Outlook 2019," 2019.
2. K. Owebor, O. E. Diemuodeke, T. A. Briggs, O. J. Eyenubo, O. J. Ogorure, and M. O. Ukoba, "Multi-Criteria Optimisation of Integrated Power Systems for Low-Environmental Impact," Energy Sources, Part A Recover. Util. Environ. Eff., vol. 44, no. 2, pp. 3459–3476, 2022, doi: https://doi.org/10.1080/15567036.2022.2064565.
3. K. Owebor, C. O. C. Oko, E. O. Diemuodeke, and O. J. Ogorure, "Thermo-environmental and economic analysis of an integrated municipal waste-to-energy solid oxide fuel cell, gas-, steam-, organic fluid- and absorption refrigeration cycle thermal power plants," Appl. Energy, vol. 239, 2019, doi: https://doi.org/10.1016/j.apenergy.2019.02.032.
4. O. J. Ogorure, C. O. C. Oko, E. O. Diemuodeke, and K. Owebor, "Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant," Energy Convers. Manag., vol. 171, 2018, doi: https://doi.org/10.1016/j.enconman.2018.05.093.
5. J. Knowles, "Overview of small and micro combined heat and power (CHP) systems," in Small and micro combined heat and power (CHP) systems, 1st ed., R. Beith, Ed. UK: Woodhead Publishing Limited, 2011, pp. 3–16.
6. S. O. Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, "Overview of energy storage in renewable energy systems," Int. J. Hydrogen Energy, pp. 1–14, 2016, doi: https://doi.org/10.1016/j.ijhydene.2016.06.243.
7. V. Masson-Delmotte, P. Zhai, H.-O. Portner, D. Roberts, J. Skea, and P. Shukla, "Global Warming of 1.5 C," An IPCC Spec. Rep. impacts Glob. Warm., vol. 1, pp. 1–9, 2018.
8. K. Owebor, E. O. Diemuodeke, T. A. Briggs, and M. Imran, "Power Situation and renewable energy potentials in Nigeria – A case for integrated multi-generation technology," Renew. Energy, vol. 177, pp. 773–796, 2021, doi: https://doi.org/10.1016/j.renene.2021.06.017.
9. FGN, "Nigeria's intended nationally determined contribution," Minist. Environ., pp. 1–23, 2015.
10. FGN, "Nigeria's First Nationally Determined Contribution - 2021 Update," Fed. Minist. Environ., pp. 1–60, 2021.
11. K. Owebor, E. O. Diemuodeke, and T. A. Briggs, "Thermo-economic and environmental analysis of integrated power plant with carbon capture and storage technology," Energy, vol. 240, p. 122748, 2022, doi: https://doi.org/10.1016/j.energy.2021.122748.
12. NERC, "Licensing, Tariff and Market Rules," Niger. Electr. Regul. Comm., 2020.
13. B. Ugwoke, S. P. Corgnatia, P. Leonea, R. Borchiellinia, and J. M. Pearc, "Low Emissions Analysis Platform Model for Renewable Energy: Community- scale Case Studies in Nigeria," Sustain. Cities Soc., vol. 67, p. 102750, 2021.