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The role of biomass in sub-Saharan Africa's fully renewable power sector – The case of Ghana

Theophilus Nii Odai Mensah*, Ayobami Solomon Oyewo, Christian Breyer

LUT University, Yliopistokatu 34, 53850, Lappeenranta, Finland

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ABSTRACT

Sub-Saharan Africa is a region with a large population living without electricity. This study investigates the grid balancing role of bioenergy in a sub-Saharan Africa's fully renewable power sector to address the energy poverty challenge in the region, using Ghana as a case country. Two methods are employed: the bioenergy estimation method, for deriving Ghana's technical bioenergy potential, and the LUT model, for the power sector transition modelling. The Ghanaian bioenergy potential of 48.3 TWh is applied on the power sector using the LUT model to develop six alternative scenarios, emphasising on the role of bioenergy, greenhouse gas emissions costs, and climate change mitigation policies. The results of the Best Policy Scenario reveal that with an electrical efficiency of 37.2%, 18 TWh of electricity, which is 16.9% of Ghana's electricity demand by 2050, could be produced from bioenergy for grid balancing. Also, the levelised cost of electricity declines from 48.7 €/MW in 2015 to 36.9–46.6 €/MWh in 2050. Whereas the cost of electricity increases to 76.4 €/MWh in the Current Policy Scenario without greenhouse gas emissions costs. The results show the viability of a relatively cheap and bioenergy balanced sustainable renewable power system for the sub-Saharan African region.

1. Introduction

In recent years, researchers have become increasingly interested in the global energy transition from a polluting and depleting fossil fuel based energy system to a renewable energy (RE) based system [1–5]. According to the International Energy Agency (IEA) [6], by 2021, the global total renewable electricity generation will exceed 7600 TWh (60%) of increase in electricity production from 2015 to 2021, of which solar photovoltaics (PV) and wind energy account for about 5700 TWh (75%) of the global renewable electricity growth [7]. The growth of RE resources in the global energy system due to cost decline [8], is a good indicator and a glimmer of hope for providing relatively clean and affordable electricity in the sub-Saharan Africa (SSA) region, which is one of the energy deficit regions in the world. To win the fight against the energy poverty challenge in SSA, a sustainable energy revolution is urgently needed. The electricity demand growth in the SSA region could be supplied with the vast RE resources available in the region [9,10].

1.1. SSA power crisis and the prospects of renewable energy

The SSA region has the lowest electricity access rate in the world, about two-third of the world inhabitants living without electricity are homed in SSA. According to the World Bank, in thirteen SSA countries, not more than 25% of people have access to electricity [11]. The demand for electricity grows twice as the global average [10]. Nearly 890 million people use traditional fuel for cooking and 600 million people lack electricity. Economic growth has been low at 3% in 2019. Sustainable development and economic growth are stifled by this dramatic lack of energy access [12–14].

In order to achieve self-sufficient, sustainable, and climate friendly power sector to conform with the Paris Agreement [10,15], the transitioning of the SSA power sector, as also discussed in the Sustainable Development Goal 7 (SDG 7) [16], is very important in reducing greenhouse gas emission (GHG). Therefore, the share of RE resources is anticipated to increase significantly in a defossilised SSA power system [10,17]. The vast renewable resources and decreasing technology costs could be a driving factor for the deployment of utility-scale and distributed PV, wind, and other renewables across the region to meet the SDG agenda by 2030 [10,18].

Moreover, the structure and generation mix of the SSA power system is less complex and costly during the transition period since

* Corresponding author.
E-mail addresses: theophilus.mensah@lut.fi (T.N.O. Mensah), solomon.oyewo@lut.fi (A.S. Oyewo), christian.breyer@lut.fi (C. Breyer).

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Nomenclature

AD	anaerobic digestion
BPS	Best Policy Scenario
CAPEX	capital expenditure
CCGT	combined cycle gas turbine
CPS	Current Policy Scenario
CO_2	carbon dioxide
CHP	combined heat and power
FAO	Food and Agriculture Organization
FLH	full load hours
FSS	Faecal sewage sludge
GT	gas turbine
GHG	greenhouse gas
HVDC	high voltage direct current
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOC	levelised cost of curtailment
LCOE	levelised cost of electricity
LCOS	levelised cost of storage
LHV	lower heating value
MSW	municipal solid waste
MW	Megawatt
OCGT	open cycle gas turbine
OPEX	operational expenditure
PURC	Public Utilities Regulatory Commission
GW	Gigawatt
LCOT	levelised cost of transmission
LNG	liquified natural gas
PV	photovoltaic
PJ	Petajoules
RE	renewable energy
RES	renewable energy sources
RoR	run-of-river
RPR	residue to product ratio
SNG	synthetic natural gas
SDG	Sustainable Development Goals
SHS	solar home systems
SSA	sub-Saharan Africa
TWh	Terawatt-hour
VRE	variable renewable energy
WACC	weighted average cost of capital
WB	World Bank

most countries in the region rely significantly on hydropower of 36 GW of the total 50 GW of renewable capacity as of 2019 according to IEA [10], and other studies [19–21].

1.2. Renewable energy potential and PV cost decline is a major driving factor

The SSA region is undoubtedly endowed with high potential of renewable energy resources such as wind, solar, hydro, and biomass. According to Ref. [22], the total RE potential in the SSA region is estimated to be around 370 PWh, 560 PWh, and 330 PWh for CSP, PV, and wind, respectively. About 12% of the world's hydropower potential is held in Africa, with a technical potential of 1800 TWh/year. The biomass potential is estimated to be up to 1649 TWh [22–24]. According to Ref. [25] the total primary energy demand in the SSA was 2700 TWh in 2015, and is projected to about 6800 TWh by 2050. The RE potential of the region is therefore capable of satisfying the demand in a fully RE system considering the available RE resource potential.

Furthermore, recent studies show that, the global weighted average levelised cost of electricity (LCOE) of utility-scale solar PV systems have reduced by 68% within a period of seven years (2010–2017) [8,26]. Examples for new record low cost for solar PV on LCOE basis can be found all around the world in countries like Abu Dhabi, Chile, Dubai, Mexico, Peru, the US and Saudi Arabia, all around 20 to 26 €/MWh [8,27], or even below, as for the case of Qatar [28] and Portugal [29]. It is estimated that, solar energy will provide about 87% of the total primary energy demand in SSA by 2050 [25], therefore, declining technology cost is a good indication that the needed energy revolution is forthcoming. Zero "use phase" GHG emissions, besides low-cost energy is the key driver for RE resources to address the two biggest problems: climate change mitigation [30–32], and the regional challenge of energy poverty [33–35].

1.3. The challenge of power grid imbalance due to variable renewables and the proposed solution

The amount of power generated by solar and wind energy varies over the hours of a day and seasons, hence the term variable renewable energy (VRE). This variability characteristic of solar and wind resources affects the stability and reliability requirements of the power grid. Solar energy has been projected to contribute about 87% of the SSA primary energy by 2050 [25]. Therefore, in the event of mass deployment of VRE in the SSA region, possible grid balancing challenges may occur [36–38] due to the variability characteristic of solar and wind resources.

In this regard, this research work, argued that sustainable modern bioenergy being a dispatchable form of energy has the potential to play a significant role in balancing the SSA power grid, beside other storage options. To test this hypothesis, this research work estimates and evaluates the sustainable bioenergy potential of Ghana and applies the yielded potential on the power sector in a fully renewable scenario for the case of Ghana [39]. Biomass is an essential source of energy in the SSA region; therefore, this research work seeks to explore the power grid balancing potential of bioenergy in SSA.

1.4. Biomass situation and usage in SSA

In this section, the categories of biomass considered for this study and their current usage in SSA are investigated. Currently, the major source of RE in the world is bioenergy [39]. It is reported that about 81.2% of the total primary energy demand in SSA (excluding South Africa), is supplied by solid biofuels and waste [24]. Biomass will continue to be an essential energy resource for SSA in the future [24]. According to Lynd et al. [40] and Ambali et al. [41], SSA has huge untapped arable land, which could provide more sustainable bioenergy potential, especially from crop residues.

The categories of biomass considered in this research include forestry (forest residues), agriculture (crop residue, and livestock manure), and municipal waste (faecal sewage sludge and municipal solid waste).

Feedstock from forestry and agriculture biomass category are mainly used in traditional form in SSA [24] and the leftovers are disposed by burning in open fields [42]. Traditional biomass is the unsuitable and often unsustainable use of fuel wood, charcoal, tree leaves, animal dung and agricultural residue for cooking, lighting, and space heating. Studies have shown that the use of traditional biomass culminates in catastrophic health problems, such as pneumonia, chronic obstructive pulmonary diseases or lung cancer [24].

Also, in SSA, livestock manure is poorly utilised for fertilizer purposes, but largely, manures are left on glazing field and are not used [43,44]. Similarly, faecal sewage sludge (FSS) is poorly managed. It is estimated that only 50% of the FSS is collected, transported, and treated. Sometimes, the uncollected FSS is discharged into the environment [43].

Furthermore, the management of municipal solid waste (MSW) in most SSA countries is not yet developed. MSW is generally defined as the waste generated and collected by municipalities and other local authorities. MSW includes mainly domestic waste, institutional, and commercial wastes. The physical composition of MSW can be biodegradable, recyclable, and non-biodegradable. It is one of the most common, yet underused sources of biomass in SSA [45,46]. It is estimated that 65% (81 million tonnes) of the total MSW (125 million tonnes) generated in Africa in 2012 was from SSA. MSW generation per capita in the region is expected to grow from 0.72 kg/capita in 2012 to 0.99 kg/capita in 2025. If the current solid waste generation rate persists, SSA is projected to substantially contribute to the global MSW generation. The most common method of disposing MSW is illegal dumping. Unlawful solid waste dumping results in GHG emissions, leachate to underground water, topsoil contamination, odour, and usually requires large space. Waste-to-Energy power plants are almost absent in the SSA region [45,47–49]. With appropriate investment in bioenergy technologies, it is estimated that 312.5 TWh (1125 PJ) in 2012 and 610.8 TWh (2199 PJ) in 2025 could have been obtained from MSW through landfill gas recovery and incineration respectively in Africa [50].

Certainly, the traditional usage and management of the above-mentioned biomass in SSA is unsustainable. The traditional form of biomass usage in the SSA region violates most of the biomass sustainability indicators [51,52], hence the need for appropriate investments in bioenergy technologies to provide a paradigm shift from traditional to sustainable modern bioenergy.

In this regard, the need to present a pathway to transform the unsustainable traditional biomass usage in SSA to a sustainable modern bioenergy usage is urgent. Sustainable modern bioenergy is defined in this research as the energy derived from sustainable biomass, i.e. biomass streams from agriculture (crop residue and livestock manure), forestry (forest residue), and municipalities (FSS and MSW), to generate power via efficient technologies to balance the power grid. The impact of sustainable bioenergy on a fully renewable power sector of SSA has not yet been studied. Therefore, this research seeks to explore the biomass streams from residues and waste of SSA and apply the yielded bioenergy potential in a fully renewable power sector scenario using Ghana as a case study. To the best of the knowledge of the authors, no other study has investigated this area of research.

1.5. Case study

Several countries in SSA share similar tropical climate conditions. This study considers Ghana as a case for the SSA region. It is assumed that the climate and energy conditions in Ghana reflect the conditions in other SSA countries. In addition, Ghana and South Africa are among the few SSA countries that have managed to achieve a high percentage of electricity access and are among the first countries to draft a sustainable energy for all (SEforAll) action plan [53].

Ghana has very good potential to harness enough energy from RE resources, especially from solar [54], wind, hydro and biomass. Studies show that the total biomass power and solar PV capacities are still comparably low in Ghana at 8 MW and 63 MW respectively by the end of 2019, according to IRENA [55] or 144 MW of PV installed capacity at the end of 2017 according to Werner et al. [56], based on a different method.

Bioenergy has been the core of the Ghanaian energy system for decades and it is expected to play a pivotal role in the future energy system of the country due to its ready availability and GHG reduction potential [57]. In order to replace fossil fuels (natural gas and oil), which emit CO_2 and trigger climate change [58,59], modern biofuels, biogas, and solid biomass could be used to relieve the Ghanaian power sector from its strong dependence on fossils. Biomass, locally produced and often close to demand, could be used in tandem with hydropower and PV systems to balance the power system affected by the variable nature of solar energy. A variety of micro combined heat and power (CHP) plants, which burn solid biomass are available. Likewise, on a domestic level, new and appropriate technologies could be developed for biomass conversion to electricity to meet local demand.

However, it is worthwhile to mention the limited availability of biomass resources due to technical and financial barriers which has been highlighted in Refs. [60,61] as a hindrance to include high shares of bioenergy in energy policy development. Likewise, the biomass demand by other sectors of the energy system such as transport and heat (industry and cooking) may limit the biomass available for power production. As a result, this power sector study has considered the sustainability criteria and has restricted the use of biomass for power generation to 35% use-factor for crop and forest residues, and 80% use-factor for livestock manures, and 80% for kitchen waste, and FSS.

With regards to Ghana's bioenergy potential, Duku et al. [62] reported a potential of 20.8 GWh (75.2 TJ) from crop residues. Kemausour et al. [63] also reported a potential of 76.4 TWh (275 PJ) and 250 TWh (900 PJ) by 2011 and 2030 respectively from residue and waste. This study focuses on using different pathways to estimate the bioenergy potential of Ghana, considering residues and waste and further apply the yielded potential on the Ghanaian power sector in a fully renewable scenario.

Technologies such as direct combustion and anaerobic digestion has been considered in this study. According to the World Bank (WB), these technologies are viable options and alternatives for developing countries [64].

It is assumed that electricity is produced via steam turbines and gas turbines for direct combustion and anaerobic digestion, respectively. Heat recovery is not considered in this study. Additional background information on Ghana is available in the Supplementary Material.

This paper is organised as follows: Section 2 presents the research methods. Section 3 presents the results. Results are discussed in detail in section 4. Conclusions and policy implications are presented in section 5. The diagram flow of the paper in shown in Fig. 1 below.

2. Research methods

Two research methods are described in this section. The bioenergy potential method is first described, and then the LUT model for the Ghana power sector transition simulation.

2.1. Bioenergy potential estimation method

This section presents the method used for the bioenergy potential estimation. Ghana is endowed with biomass resources, which includes crop residues, wood waste, MSW, animal waste, algae, sewage sludge, and aquatic plants [62,63,65]. In order to avoid violation of biomass sustainability criteria, three main biomass sources are considered, namely, forestry (forest residues),

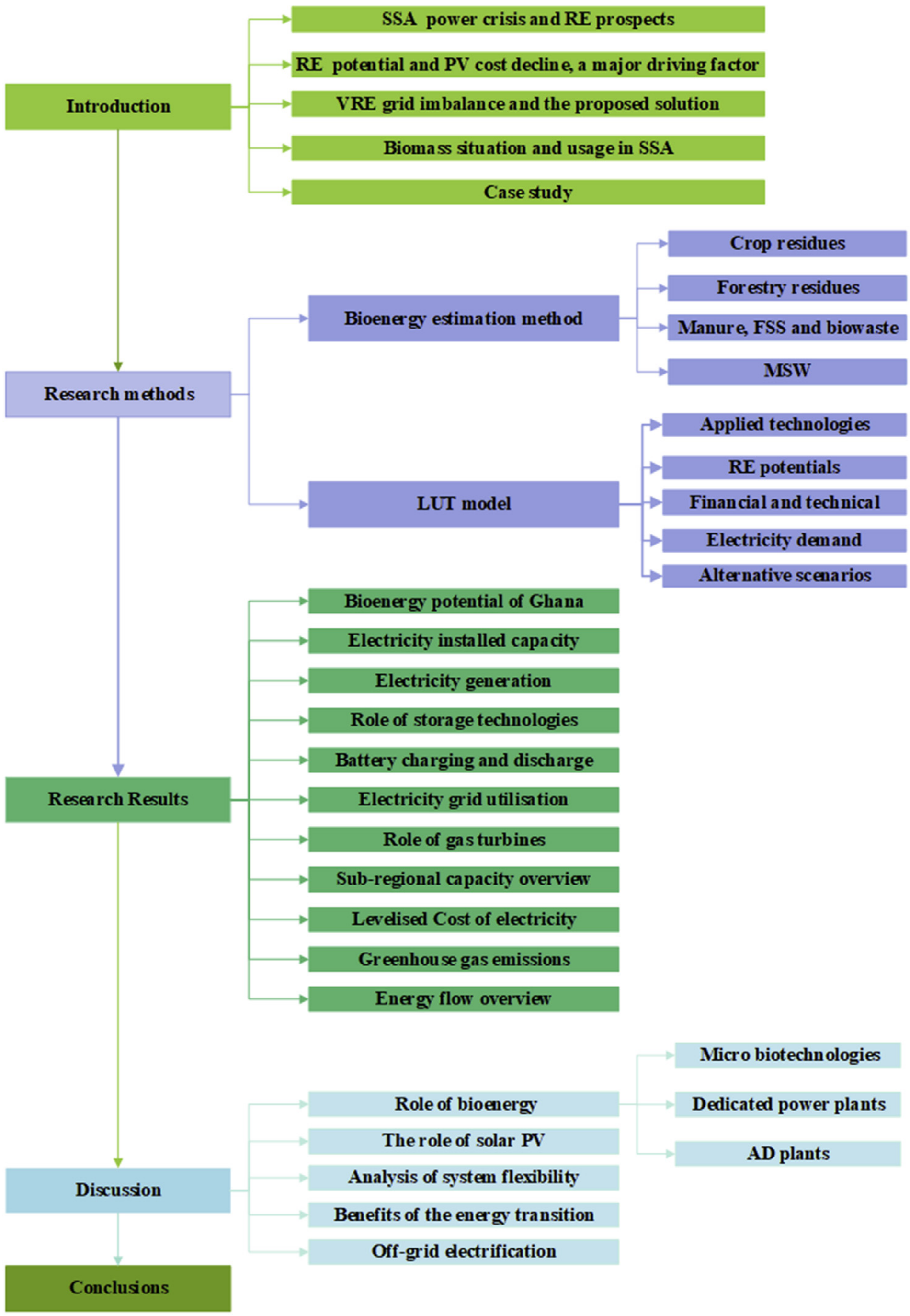

Fig. 1. Flow chart of the paper.

agriculture (crop residue, and livestock manure), and municipal waste (MSW and FSS). Algae, aquatic plants, energy crops and industrial residue are not considered in the bioenergy calculations.

The data obtained for the case of Ghana are from literature.

Fig. 2 shows the methodological pathways for the bioenergy potential estimation and evaluation.

Residues with less moisture content such as crop residues, wood residue, and MSW (excluding food waste) are treated with direct combustion technology, while those with high moisture content such as kitchen or food waste, livestock manure, and FSS are treated with anaerobic digestion technology.

2.1.1. Energy potential of crop residues

Energy from crop residues is calculated based on FAO data [66] for the Ghanaian crop production in 2015. The residue to product ratio (RPR) [67] parameter is used to estimate the amount of residues available based on the reported product yields. All energy units are accounted for the lower heating value (LHV) obtained

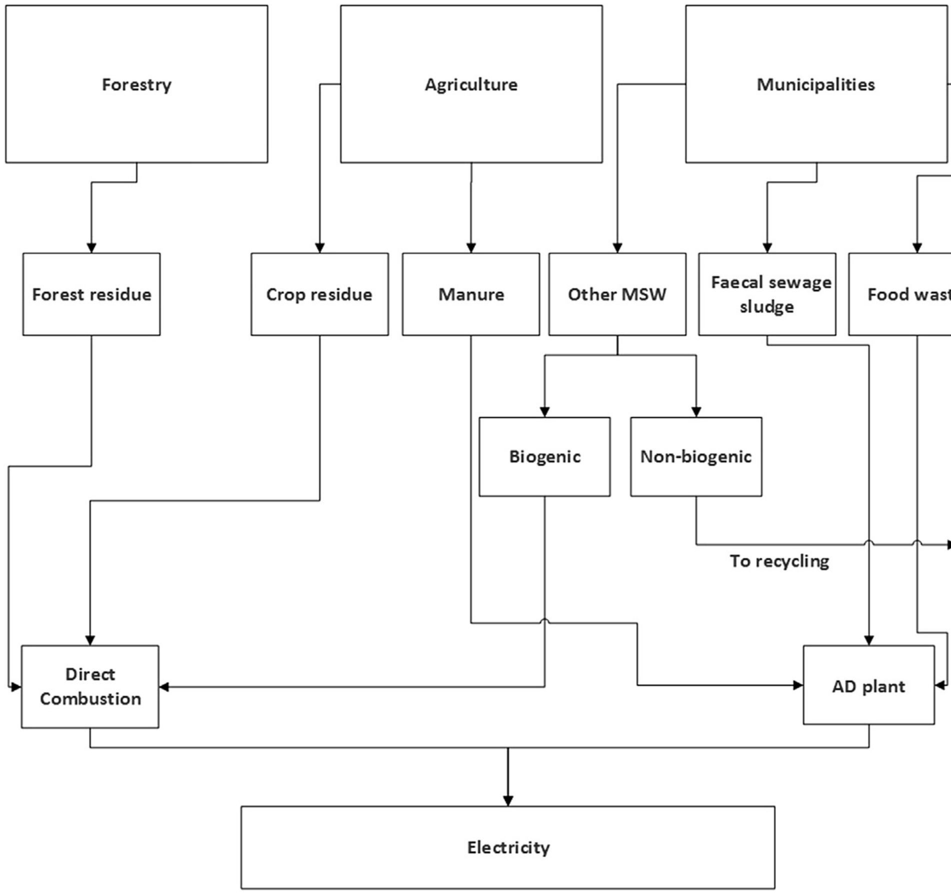

Fig. 2. Bioenergy potential estimation methodological pathways.

from Ref. [68]. It is assumed that the availability or use factor for residues is 35% [69] for the case of Ghana. Annual crop residue energy potential is calculated according to Eq. (1).

$$E_{CR} = \sum_{i=1}^{n}(CP_i \cdot RPR_i \cdot LHV_i \cdot fuse) \tag{1}$$

where (E_{CR}) is energy potential of crop residue per annum, (*CP*) is crop production for the reference year 2015, (*RPR*) is the residue to product ratio of a crop and (n) represents the total number of crops considered. (*LHV*) is the lower heating value of a specific crop residue and (*fuse*) is the use factor.

2.1.2. Energy potential of wood residues

For wood residues, the annual bioenergy potential is calculated according to Eq. (2).

$$E_{FR} = \sum_{i=1}^{n}(WP_i \cdot RPR_i \cdot LHV_i \cdot fuse) \tag{2}$$

where (E_{FR}) is the energy potential of forest residues per annum, (*WP*) is the total wood production for the reference year [70]. (*RPR*) is the residue to product ratio of a wood type [68] and (n) represents the total number of wood types considered. (*LHV*) is the lower heating value of specific wood residue [71] and (*fuse*) is the use factor.

2.1.3. Energy potential of livestock manure, FSS, and organic biowaste

The amount of livestock manure available for bioenergy is estimated based on manure per head of livestock per annum [72] and applied for the case of Ghana based on FAO [73] data on livestock for a reference year. The use factor for livestock manure is assumed to be 80% for the case of Ghana. FSS is estimated based on population data and specific faeces per person per annum. Respective data for Ghana is extracted from Ref. [74]. Bio-waste (kitchen waste) is estimated by population and generation per capita per annum [75].

Annual availability of livestock manure, FSS and food waste is estimated according to Eqs. (3)–(5) respectively. The total biodegradable feedstock allocated for anaerobic digestion is calculated with Eq. (6).

$$M_a = \sum_{i=1}^{n}(P_a \cdot M_i \cdot fuse) \tag{3}$$

$$S_s = (P_h \cdot H_f \cdot f_{use}) \tag{4}$$

$$Q_{bw} = (W_{bio} \cdot P_h \cdot f_{use}) \tag{5}$$

$$F_i = (M_a + S_s \cdot Q_{bw}) \tag{6}$$

where (M_a) is the manure available per annum, (P_a) is the animal population per annum, (M_i) is the manure per head per annum in tonnes, (n) is the categories of livestock considered, and (*fuse*) is the use factor of 80% for Ghana. (S_s) is FSS available per annum, (P_h) is human population as of the chosen reference year, and (H_f) is faeces per capita per annum, (Q_{bw}) is the total bio-waste (food waste), (W_{bio}) is the bio-waste generation per capita per annum, (P_h) is the human population and (F_i) is the total feedstock.

Livestock manure, FSS, and organic bio-waste (food and garden waste) are treated with anaerobic digestion to maximise the biogas output due to high moisture content. The energy content of the biogas is estimated with Eq. (7) below.

$$E_{BG} = \sum_{i=1}^{n} (F_i \cdot T_{s,i} \cdot V_{s,i} \cdot Bio_{vs,i} \cdot C_{CH_4} \cdot LHV_{CH4}) \tag{7}$$

where (E_{BG}) is the estimated energy content of biogas per annum, (F_i) is the total feedstock, (T_s) is the total solid share of the feedstock, factored in as a percentage value, (Vs) is the volatile solid share of the total solid, (Bio_{vs}) is the biogas yield per tonne of volatile solid, (C_{CH4}) is the methane content of biogas, (LHV_{CH4}) is the lower heating value of methane [76–78].

2.1.4. Energy potential of MSW

MSW generation per capita is obtained for the case of Ghana from Ref. [75]. MSW is assumed to be treated with an incineration process for bioenergy use. Organic bio-waste (food and garden waste) is assumed to be source-separated and treated in an anaerobic digestion process described in Eq. (5). Since the focus is renewables, only the biogenic share of the MSW is considered. Biogenic part of the MSW is the fraction of MSW which is considered to be biomass originated and therefore, considered as renewable. Examples of such fractions includes paper and cardboard, pampers, textiles from plants, rubber from plants, used wood, paper packaging, and leather [79]. The energy potential of the biogenic MSW is estimated according to Eq. (8).

$$E_{MSW} = (Q_{MSW} \cdot P_h \cdot MSW_{bio} \cdot LHV_{MSW}) \tag{8}$$

where (E_{MSW}) is the total energy potential of MSW per annum, (Q_{MSW}) is the MSW generation per capita per annum (excluding food waste which is already accounted in Eq. (5)), (P_h) is the population for the reference year, (MSW_{bio}) is the biogenic share of the MSW [80], and (LHV_{MSW}) is the lower heating value of mixed MSW fractions [50]. It is assumed that all non-biogenic fractions are recycled.

The main feedstocks considered for the Ghanaian bioenergy estimation is presented in Table 1 below.

The total bioenergy harnessed from the above feedstock is calculated with Eq. (9).

$$E_{BIO} = E_{CR} + E_{FR} + E_{BG} + E_{MSW} \tag{9}$$

The obtained technically harvestable bioenergy potential of Ghana is then applied on the Ghanaian power sector in fully renewable scenarios using the LUT model which is described below.

2.2. LUT Energy System Transition model

The Ghanaian power sector is modelled with the LUT Energy System Transition model described in Ref. [1]. The 16 administrative regions of Ghana are merged into six sub-regions forming six nodes in the model. The six sub-regions are:

- Eastern-Coastal (GH-EC): Greater Accra, Volta and Oti regions
- Western-Coastal (GH-WC): Central, Western and Western North regions
- Central (GH-CEN): Eastern and Ashanti regions
- Brong Ahafo (GH-BA): Bono, Ahafo and Bono East regions
- Northern Territory (GH-NT): Northern, North East and Savannah regions; and
- Upper North (GH-UN): Upper East and Upper West regions.

These sub-regions are interconnected through a power transmission grid as depicted in Fig. 3.

The LUT Energy System Transition model, in short LUT model, is a linear optimisation tool, which performs an hourly resolution of the energy system with parameters for an entire year, under certain operational constraints and assumptions for the future RE powered system and demand. The principal objective of the model is to reduce the energy system total annualised cost. The energy system annualised cost comprises of the following: annualised capital expenditures of all installed technologies, operational expenditures, and fuel costs if applicable for all electricity generation and storage technologies and cost of generation ramping per annum. Fig. 4 shows the input and output parameters of the LUT model. Detailed model description, applied constraints and equations can be found in Bogdanov et al. [1].

In addition, the energy system planning includes residential, commercial and industrial PV prosumers, as studied in detail in Keiner et al. [82]. Depending on the cost, prosumers can decide to purchase electricity from the national grid or to install rooftop PV and Lithium-ion batteries for self-consumption, thereby prosumers

Table 1
Main contributors and sub-contributors for Ghana's bioenergy potential.

Index	Crop residue	Wood residue	Biogas	MSW
1	Sorghum	Wood fuel non-coniferous	Cattle manure	Paper
2	Millet	Saw logs and veneer logs	Goats manure	Leather
3	Rice	Industrial round wood coniferous	Pigs manure	Rubber
4	Sugarcane	Industrial round wood non-con	Poultry manure	Textiles
5	Beans	Wood charcoal	Sheep manure	Inert
6	Cashew nuts, shell		Sewage sludge	Miscellaneous
7	Sweet potatoes		Food bio-waste	
8	Groundnuts			
9	Yam			
10	Banana			
11	Plantain			
12	Coconut			
13	Oil palm fruit			
14	Coffee			
15	Cocoa			
16	Cassava			
17	Maize			

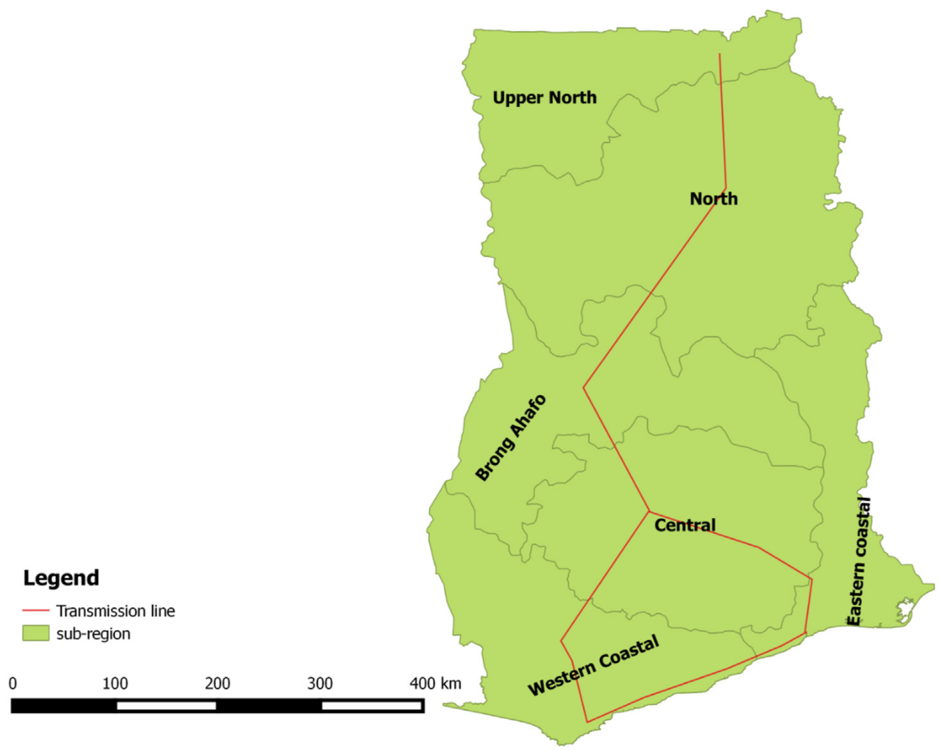

Fig. 3. The six sub-regions of Ghana and power transmission grid configuration.

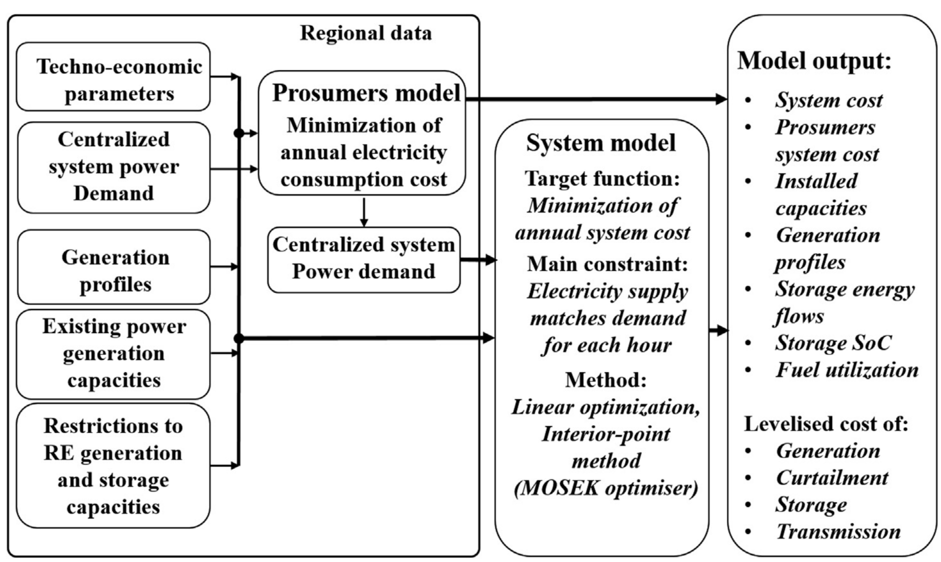

Fig. 4. Flow diagram of the LUT model [81].

can also sell generated excess electricity to the national grid for 0.02 €/kWh. The principal function of prosumers is to reduce the cost of consumed electricity. The total prosumer cost includes cost of self-generation, cost of grid electricity consumed and income for the sold excess electricity.

The model operates under certain constraints:

1. No new fossil-based power plants are installed after 2015 in the Best Policy Scenario. The existing fossil-based power plants are phased out when their economic lifetime expires. This excludes gas turbines. The installation of gas turbines is allowed after 2015 due to its lower GHG emissions, higher efficiency, and most importantly its ability to switch to biofuels and synthetic natural gas; which is actually necessary for the transition period and the zero GHG emission target.
2. To prevent system disruptions, the growth of RE capacity share cannot exceed 4% per year. This growth in share is limited to 3% between 2015 and 2020.
3. The prosumer demand is limited to 20% of the total demand, excess generation can be fed into the grid, but not more than 50% of total PV prosumer generation. The prosumer generation is constrained in a stepwise progression from a maximum of 3%

in the initial time step to 6%, 9%, 15%, 18% and 20% in the subsequent time steps.

4. Bioenergy constraint is set to regulate the biogas and waste resource potentials that could be exploited, 33% by 2020, 66% by 2025, and 100% by 2030 onwards. This constraint limits bioenergy technologies from being installed too quickly.

2.2.1. Applied technologies

The main technologies applied for the Ghanaian power sector modelling include electricity generation, power transmission, storage, and energy bridging technologies. Existing transmission grid capacity was taken from West African Power Pool [83], transmission and distribution grid losses were considered according to Sadovskaia et al. [84] and electricity load profiles were taken from Toktarova et al. [85]. The storage solutions comprise of battery, pumped hydro energy storage (PHES) [86], adiabatic compressed air energy storage (A-CAES) [87], and power-to-gas (PtG) storage [88], including electrolysers, CO_2 direct air capture [89], methanation and gas turbines. Fig. 5 shows the block diagram for the energy transition model.

2.2.2. Renewable energy potential

Several RE resources were considered for this study to ascertain the maximum potential that could possibly be harnessed to provide Ghana with long-term energy security. Key RE resources considered for this research include, solar, wind, hydro, and biomass. Geothermal, wave and tidal are not considered.

The feed-in profiles for solar PV (single-axis tracking and optimally tilted), onshore wind energy and concentrating solar thermal power (CSP) are calculated according to Refs. [81,90], based on resource data from NASA [91,92], reprocessed by the German Aerospace Centre [93]. The feed-in profile for hydropower is estimated based on monthly resolved precipitation data for the year 2005 as normalised sum of precipitation in the regions [94]. Resource potential for bioenergy is estimated according to the introduced method already described in section 2.1. Additional information on full load hours for all recourses are available in the Supplementary Material (Tables A1-A6 and Figure A3) and generation profiles in Supplementary Material (Figure A4).

2.2.3. Financial and technical assumptions

The technical and financial assumptions for all the energy system technologies, components, and sub-components are made in 5year time intervals and is provided in the Supplementary Material (Table A14). This includes the capital expenditure (CAPEX), operational expenditure (OPEX), and lifetime from 2015 onwards. For calculating the financial returns on investment, weighted average cost of capital (WACC) is set to 7% except for residential PV prosumers, which is set to 4% owing to lower returns on investment requirements.

Technical assumptions regarding power generation efficiency, storage facilities, HVAC power line losses and converters is presented in Supplementary Material (Table A15-A17). The electricity prices for residential, commercial, and industrial end-users for the base year 2015 were obtained from Public Utilities Regulatory Commission (PURC) of Ghana [95]. The electricity prices were calculated until 2050 based on [96,97]. Electricity prices applied are presented in Supplementary Material (Table A18).

The RE upper limits were calculated based on Bogdanov and Breyer [98] and lower limits were retrieved from Farfan and Breyer [99].

2.2.4. Electricity demand

The electricity demand for Ghana is projected based on IEA demand growth rate for West Africa obtained from Ref. [100]. The electricity demand projection until 2050 can be found in the Supplementary Material (Table A18). The hourly load profile is estimated according to Toktarova et al. [85].

2.2.5. Alternative scenarios

Six power sector scenarios were developed in this study as described in Table 2. The principal objective is to run a Best Policy Scenario (BPS) with bioenergy and without bioenergy to investigate the effects and significance of dispatchable bioenergy for

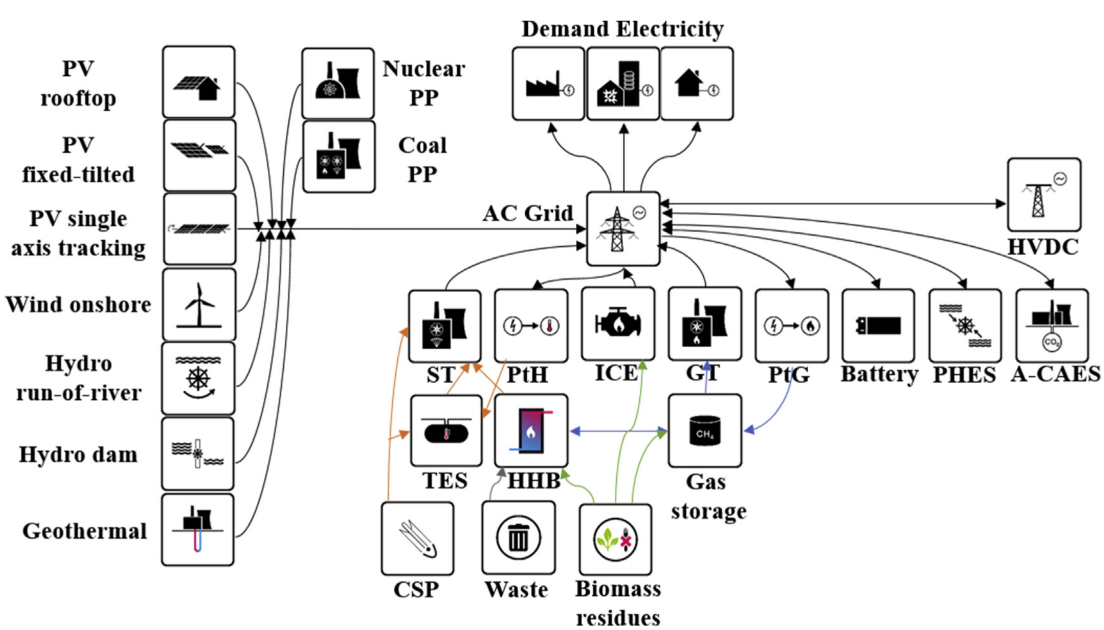

Fig. 5. Block diagram of the LUT Energy System Transition model for the power sector [81] Abbreviations: PP, power plant, ST, steam turbines, PtH, power-to-heat, ICE, internal combustion engine, GT, gas turbines, A-CAES, adiabatic compressed air storage, PtG, power-to-gas, PHES, pumped hydro energy storage, TES, thermal energy storage, HHB, hot heat burner, CHP, combine heat and power.

Table 2
Scenarios description.

Scenario	Description
Best Policy Scenario (BPS-1)	A 100% RE scenario with bioenergy and GHG emission cost
Best Policy Scenario without GHG emission cost (BPS-1noCC)	A 100% RE scenario with bioenergy without GHG emission cost
Best Policy Scenario (BPS-2)	A 100% RE scenario without bioenergy, with GHG emission cost
Best Policy Scenario without GHG emission cost (BPS-1noCC)	A 100% RE scenario without bioenergy without GHG emission cost
Current Policy Scenarios (CPS)	This scenario considers Ghana's proposed energy targets relating the power generation capacity mix to the year 2030 [76]. Subsequent years after 2030 to 2050 are extrapolated accordingly.
Current Policy Scenario without GHG emission cost (CPSnoCC)	Current Policy Scenario without GHG emission cost.

balancing the power sector with large shares of VRE resources. BPS-2 is a 100% RE scenario without bioenergy, but with GHG emission cost. This scenario was necessary to highlight the importance and benefits of modern bioenergy, and how it could be utilised to serve the national grid, than just for heating and cooking purposes, as practiced currently in Ghana and other SSA countries [24]. It is reported by Ref. [101], that less efficient and unsustainable traditional biomass and solid waste supply about 39.8% of Ghana's total primary energy demand. With the appropriate investments in bioenergy technologies, modern biomass could be more efficiently used for grid balancing as illustrated by the BPS-1 in section 4.3. The Current Policy Scenario (CPS) is modelled according to the current government plan [102] to investigate the financial and technical future implications of a business-as-usual case. In addition, the BPSs and CPS were simulated without GHG emission cost, to observe the impact of non-application of GHG emission cost on the transition. It is worth mentioning that the BPS without GHG emission cost is not expected to reach 100% RE.

3. Research results

This section presents the main findings of the research. Results of scenarios without GHG emission cost are not presented in this section due to similarities with scenarios with GHG emission cost. However, difference in key parameters and financial results for all scenarios are discussed in section 4.4.

3.1. Estimated bioenergy potential of Ghana

The results of the bioenergy estimation for Ghana is presented in Table 3. As observed in Table 3 above, the energy potential of different feedstocks is dominated by crop residue of 29.1 TWh, forest residue of 10.9 TWh, biogas of 5.3 TWh and MSW of 2.9 TWh. The total bioenergy harnessed is 48.3 TWh which is applied on the Ghanaian power sector in a fully renewable scenario using the LUT model. The results of the LUT model simulation is discussed below. Additional information on Ghanaian bioenergy potential is available in the Supplementary Material (Tables A7-A13).

Table 3
Ghanaian bioenergy potential in 2015.

Feedstock	tonne/a	Energy (PJ)	Energy (TWh)
Crop residue	5,976,634	104.6	29.1
Forest residue	2,821,729	39.5	10.9
Manure, bio-waste, sewage sludge	35,120,151	19.2	5.3
MSW	1,853,255	10.7	2.9
Total	45,771,769	174.0	48.3

3.2. Electricity installed capacity

Investments in the Ghanaian power sector are required to meet the future energy demand. Fig. 6 presents the installed capacities during the transition period. Fig. 6 (a)–(b) illustrates the installed capacities in the BPSs. The result indicates the dominance of solar PV during the transition. Solar PV contributes 47 GW (85%) in BPS-1 and 62 GW (93%) in BPS-2 by 2050. Besides solar PV, bioenergy, hydropower, and gas turbines are included in the generation mix. Fig. 6c illustrates the capacity development in the CPS. In the CPS, gas turbines and hydropower dominate the power sector until 2030. Solar PV and wind energy capacities are increased from 2035 onwards. By 2050, gas turbines dominate with 13 GW, followed by solar PV with 5 GW, wind energy with 2 GW and hydropower with 2 GW. The total installed capacities in the CPS is 22 GW, BPS-1 is 56 GW and BPS-2 is 67 GW by 2050. The plausible reason for lower capacities in the CPS is due to the influence of gas turbines running on high full load hours (FLH), followed by BPS-1 due to the influence of biomass plants, whereas higher installed capacity is required in BPS-2 due to solar PV FLH being comparably lower to other technologies. Essential power capacities needed during the transition is presented in Supplementary Material (Tables A19-A24).

3.3. Electricity generation

The electricity generation of the BPSs and the CPS is shown in Fig. 7 below. Fig. 7 (a)–(b) depicts the electricity generation mix in the BPSs. In the BPS-1, solar PV dominates the electricity supply with 84 TWh (76%), followed by bioenergy with 18 TWh (15%) and hydropower with 9 TWh (8%) by 2050, whereas in BPS-2, solar PV dominates with 113 TWh (92%) and hydropower 9 TWh (7%). Fig. 7c illustrates the generation in the CPS, which is dominated by gas turbines and hydropower until 2030. By 2050, gas turbines dominate with 87 TWh, followed by solar PV with 10 TWh and hydropower with 8 TWh. The total generation in the BPS-1 is 113 TWh, BPS-2 is 125 TWh and 107 TWh in CPS by 2050. Additional information on electricity generation is available in the Supplementary Material (Figure A5).

3.4. Role of storage technologies

The role of storage technologies increases with the shares of variable RE during the transition. Fig. 8 depicts the storage output under various scenarios. The storage output is 38 TWh in BPS-1, 52 TWh in BPS-2 and 5 TWh in CPS, respectively. Battery dominates the storage output in all scenarios. In BPS-1, prosumer battery dominates until 2035, followed by utility-scale battery from 2035 until 2050 as shown in Fig. 8a. In BPS-2 utility-scale battery dominate total storage output, followed by prosumer battery, TES and gas storage by 2050 as shown in Fig. 8b.

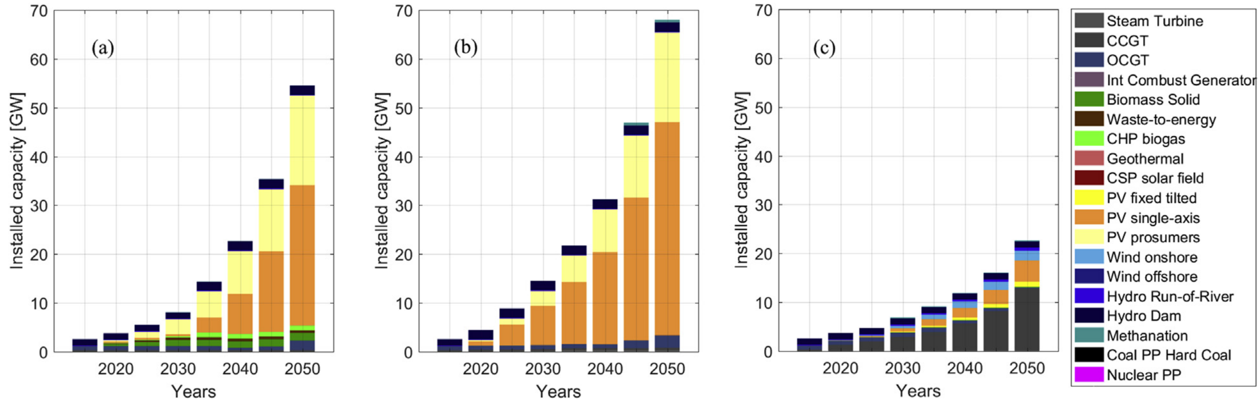

Fig. 6. Cumulative installed capacities in the BPS-1 (a), BPS-2 (b) and CPS (c) from 2015 to 2050.

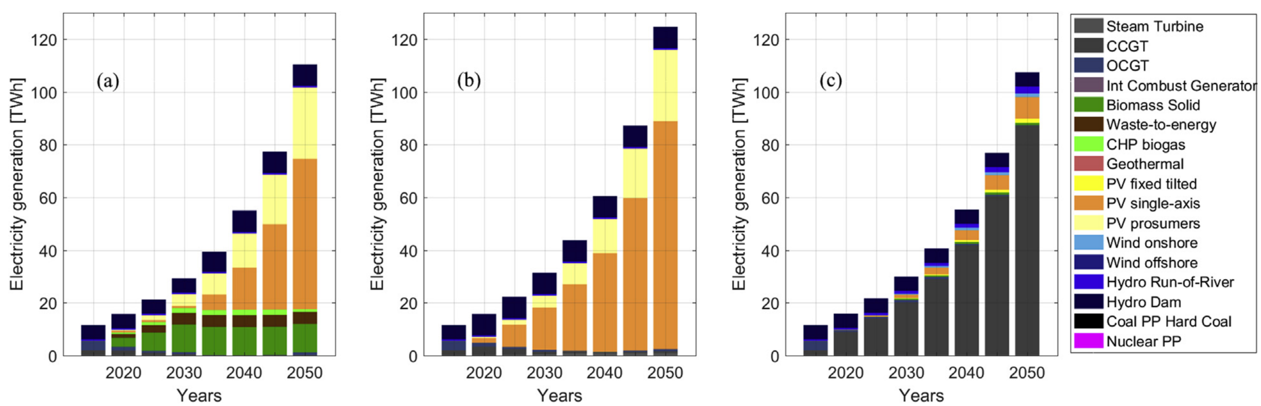

Fig. 7. Electricity generation mix by different technologies in the BPS-1 (a), BPS-2 (b) and CPS (c) from 2015 to 2050.

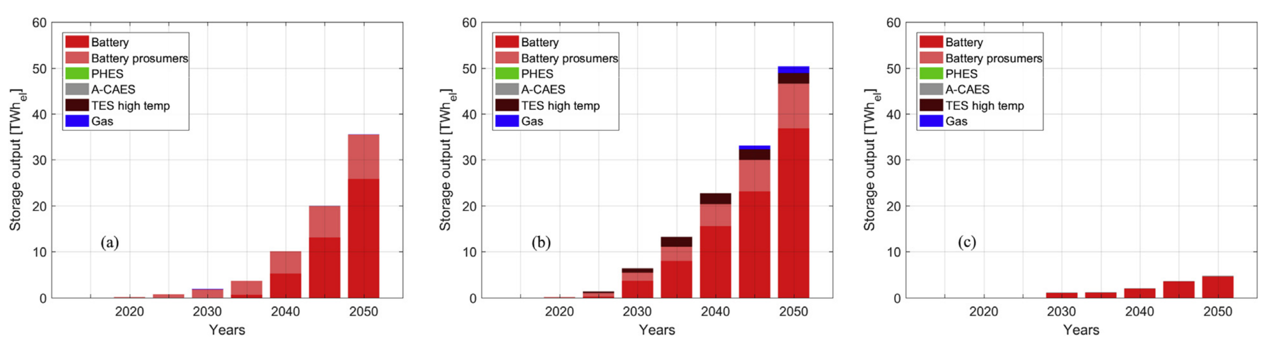

Fig. 8. Storage technologies' output in the BPS-1 (a), BPS-2 (b) and CPS (c) from 2015 to 2050.

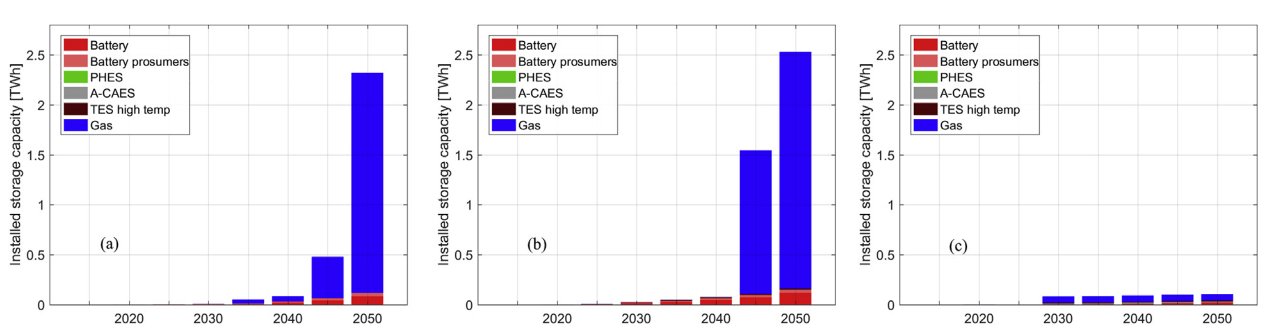

Fig. 9. Installed storage capacity in the BPS-1 (a), BPS-2 (b) and CPS (c) from 2015 to 2050.

Whereas, in the CPS utility-scale battery appears to be more relevant from 2030 onwards supported by a little share of A-CAES as shown in Fig. 8c.

Gas storage dominates the storage capacity during the transition in all scenarios considered particularly in the BPSs from 2045 onwards as shown in Fig. 9. Higher share of gas storage in the BPSs is required for seasonal balancing. The relevance of storage technologies appears to be stronger in the BPSs than in the CPS, due to high shares of RE in the BPSs.

3.5. Battery charging and discharge

The battery-to-PtG effect [36,103,104], can be observed as a means to reduce total system cost in an energy system with very high VRE shares, leading to a higher overall energy system efficiency. Battery is used to charge the gas storage via utilisation of electrolysers in off-peak hours, as demonstrated in the BPS-2 and depicted in Fig. 10. The battery powers the methanation process during low demand hours to produce synthetic natural gas (SNG) for long-term storage in order to reduce total curtailment and PtG charging capacities, and to maximise PtG FLH and reduce total energy system cost. Undischarged batteries in the morning of a sunny day would lead to curtailment of solar PV electricity, which can be effectively avoided via the battery-to-PtG effect. In addition, biomethane produced via anaerobic digestion, as shown in Eq. (7), complements the gas supply in low sunshine seasons and is delivered via a common gas grid. Additional information on curtailment can be found in the Supplementary Material (Figure A6). The discharged battery is recharged during the day when solar PV production is high. The electricity transferred from battery to PtG is 1.6 TWh in BPS-2 representing 2% of the total electricity demand in the BPS-2. Additional information on the state of charge of various technologies are available in the Supplementary Material (Figures A7-A9).

3.6. Electricity grid utilisation

The power exchange of BPS-1 and CPS is discussed in this section. Grid interconnections provide further flexibility to the power sector. The grid structure in the BPS-1 is the opposite of the CPS. Fig. 11 shows the electricity exchange in the BPS-1 and CPS. In the BPS-1, most of the generation occurs in the northern region (GH-UN) and is transmitted via transmission power lines to the central and southern regions, whereas the opposite is observed in the CPS.

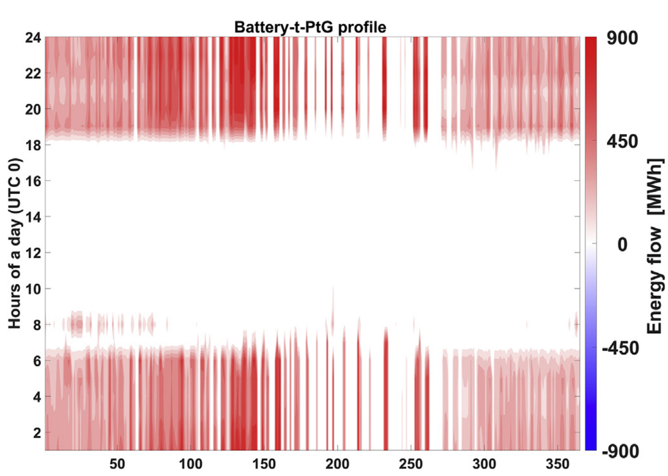

Fig. 10. Profile of battery discharge to PtG in the BPS-2 in 2050.

Electricity exchange in the BPS-1 is shown in Fig. 11 (left) and comprises about 29 TWh (77% of local generation) of exports from GH-UN by 2050. GH-UN is the main power production hub of Ghana in a fully RE power sector. Whereas in the CPS, GH-EC and GH-CN emerge as the main exporting regions as shown in Fig. 11 (right). The net grid transfer in the BPS-1 is 30 TWh, representing 28% of the total electricity demand, compared to 20 TWh representing 18% in the CPS. In Fig. 11 the size of the arrow flows specifies the value of power transmitted between respective regions. The ribbons and flows of the exporter and importer regions respectively have the same colour. Taking the BPS-1 grid exchange (Fig. 10 left) for example, the electricity flow for region GH-EC is coloured green and that of GH-CN is coloured yellow. In a power exchange between these two regions, an exporting region (GH-EC) extends a green flow, yellow ribbon of export to GH-CN. Additional information on grid utilisation profiles is presented in the Supplementary Material (Figure A10).

3.7. Role of gas turbines

Gas turbines are found to be relevant flexible technologies due to their ability to cover a large time scale of frequency variation. Gas turbines are an ideal balancing technology in the energy transition period towards 100% renewables. In the BPSs, gas turbines are permitted to be installed after the 2015 reference year, owing to lower GHG emissions and high probability to replace fossil natural gas with SNG and biomethane. The generation profiles of gas turbines (OCGT and CCGT) in the BPS and CPS are illustrated in Fig. 12. By 2050, gas turbine installed capacity is 2 GW in the BPS-1, 3 GW in the BPS-2 and 13 GW in the CPS. Gas turbines are only needed in the BPSs during the West African monsoon season, which is most heavy during the months of June to September. Whereas in the CPS, CCGT functions more as base generation power plant and OCGT contribution is required during the night times. The FLH for the gas turbine decreases from around 4890 in 2015 to 515 in the BPS-1 and about 470 in the BPS-2 by 2050. Fig. 13 shows the usage of SNG and bio-methane to operate gas turbines in the periods of low sunshine in Ghana, during the monsoon period in the BPS-1. Charging of the gas storage occurs throughout the year and is discharged at peak during the monsoon period.

3.8. Sub-regional capacity overview in a 100% renewable energy system

Fig. 14 shows the RE installed capacities projection across the country in the BPSs by 2050. GH-UN is the dominating sub-region with installed capacity of 18 GW in the BPS-1 and 27 GW in the BPS-2, as shown in Fig. 14a and b, respectively. Most of the capacity installed is solar PV due to high solar resource potential in this region. The overall installed capacities in the BPSs is dominated by solar PV single-axis tracking followed by optimally tilted PV. Bioenergy, hydropower, and gas turbines complement solar PV generation. Additional information on regionally installed capacities and generation is available in the Supplementary Material (Figures A11-A14).

3.9. Levelised cost of electricity

The main contributors to the total energy system LCOE can be seen in Fig. 15. The LCOE includes the cost for generation, transmission, GHG emissions, storage, curtailment, and fuel cost. Fig. 15 (a)–(b) show the LCOE in the BPSs during the transition period. The LCOE declines significantly from 48.7 €/MWh in 2015 to 37.0 €/MWh and 46.6 €/MWh in the BPS-1 and BPS-2 respectively by 2050. In the CPS, LCOE increases from 48.67 €/MWh to 120.5

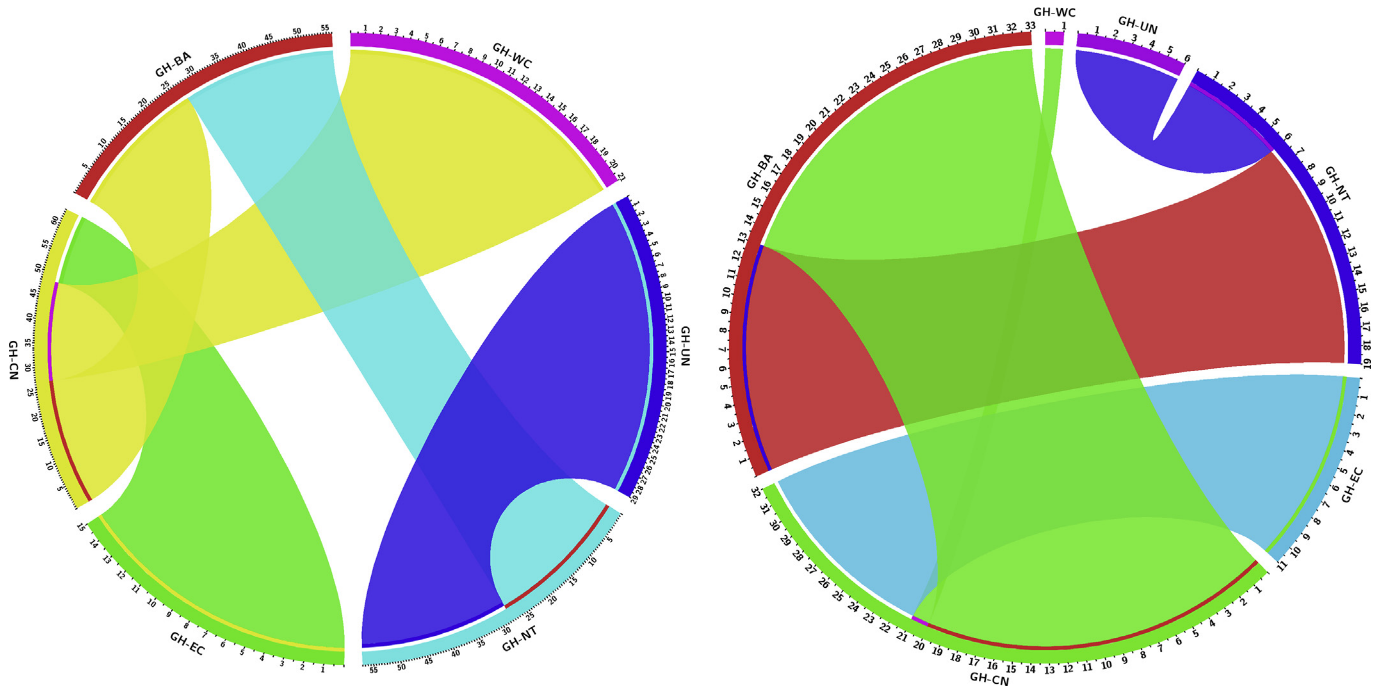

Fig. 11. Power exchange across the country in the BPS-1 (left) and CPS (right) by 2050.

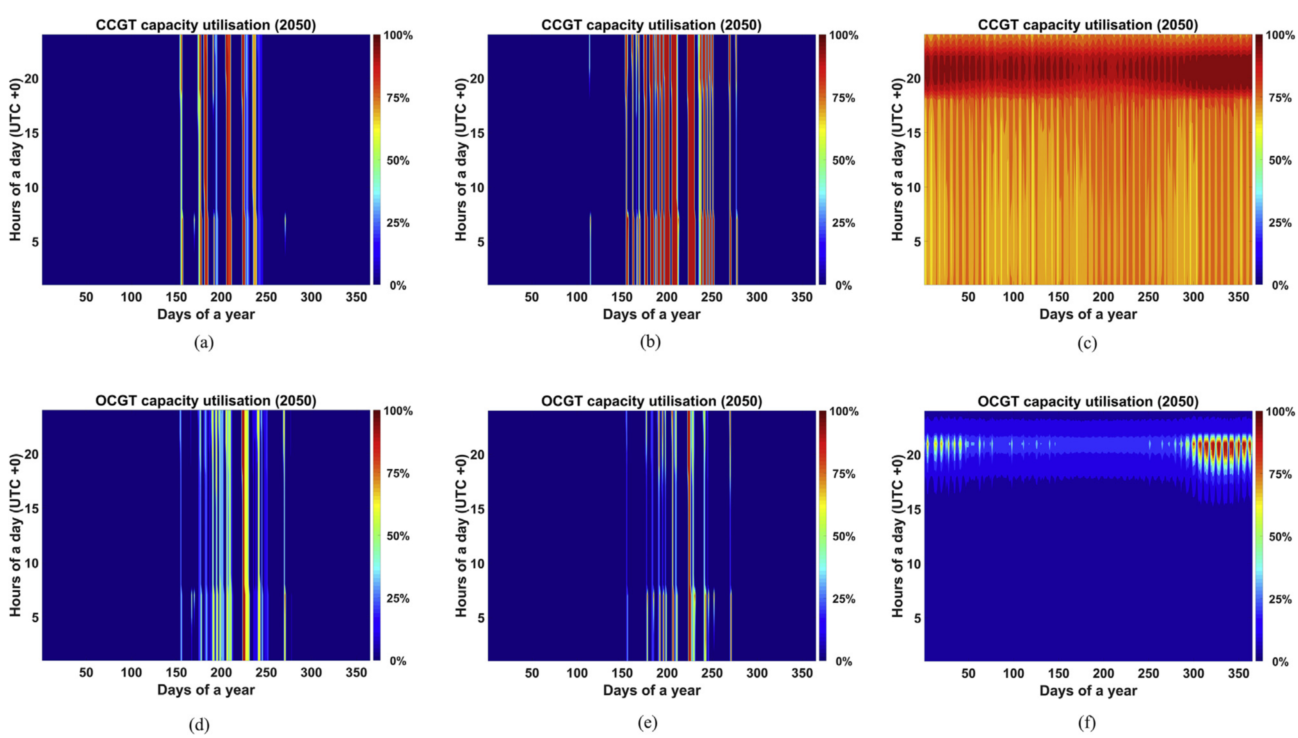

Fig. 12. Combined cycle gas turbine profiles in the BPS-1 (a), BPS-2 (b), and CPS (c); and open cycle gas turbine profiles in the BPS-1 (d), BPS-2 (e) and CPS (f) in 2050.

€/MWh as shown in Fig. 15c. Contributing components such as fuel cost and GHG emissions cost decline from 2015 and finally diminishes by 2050, in the BPSs. But storage cost increases significantly from 2030 onwards in both BPSs. The reverse situation is observed in the CPS where fuel and GHG emissions cost increase from 2015 to 2050. This can be attributed to the high presence of fossil natural gas and oil thermal power plants in the current Ghanaian power generation mix. The cost structure of the CPSs is greatly influenced by fuel and GHG emissions cost, which keeps increasing annually. Additional results on costs for all scenarios are available in the Supplementary Material (Table A25 and Figures A15-A18).

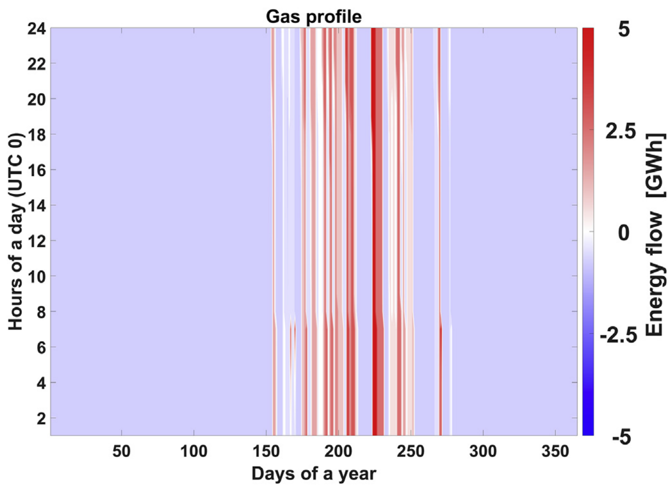

Fig. 13. Gas storage profile during an entire year in the BPS-1 for 2050.

3.10. Greenhouse gas emissions

The GHG emissions trend during the transition for all scenarios is shown in Fig. 16. Fast emissions reduction is achieved in the BPSs. GHG emissions decline from around 2.5 Mt_{CO2eq} in 2015 to 0.4 Mt_{CO2eq} in BPS-1 and to 0.8 Mt_{CO2eq} in BPS-2 by 2030, and further decline to zero in both scenarios by 2050, as shown in Fig. 16 (a)–(b). Whereas GHG emissions in the CPS increase from 2.5 Mt_{CO2eq} in 2015 to 31 Mt_{CO2eq} in 2050 as shown in Fig. 16c.

3.11. Energy flow overview

Fig. 17 illustrates the system energy flow in the 2015 reference scenarios (top) and BPS-1 by 2050 (down). It demonstrates the flow of the primary energy resources, conversion technologies, storage technologies, final electricity demand, grid, and grid losses. In the reference scenario, Fig. 17 (top), the primary energy consists of about 67% fossil fuels, which diminishes completely in the BPS-1 by 2050 as depicted in Fig. 17 (bottom). In the BPS-1, Fig. 17 (bottom),

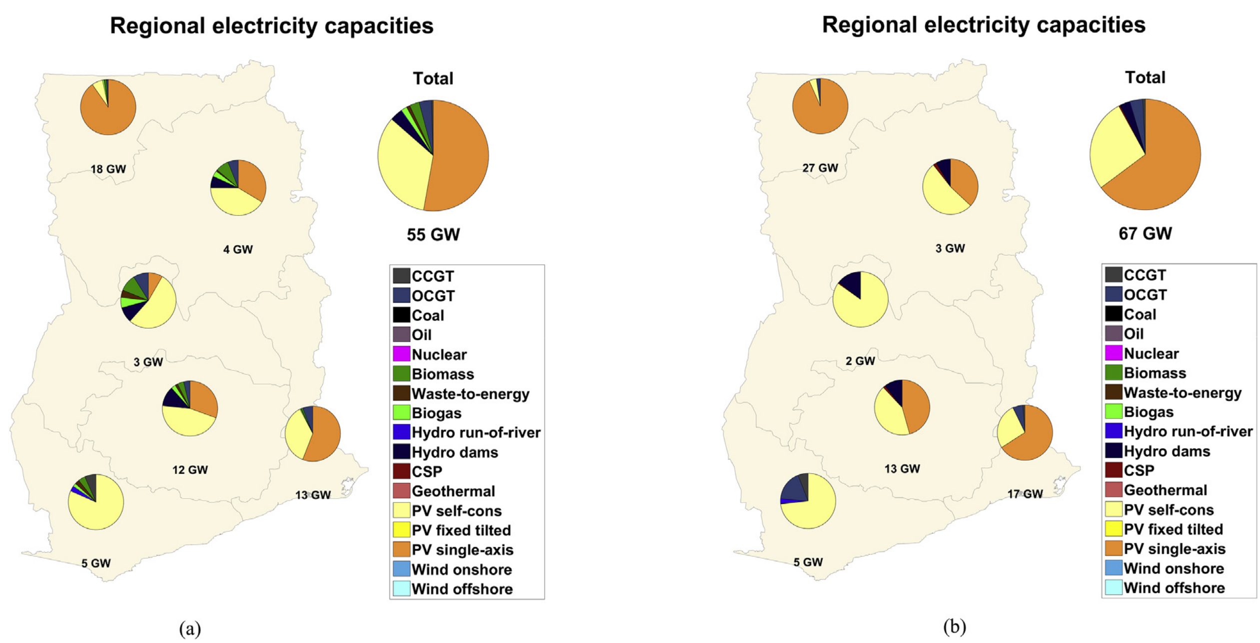

Fig. 14. Sub-regional RE installed capacities for the BPS-1 (a) and BPS-2 (b) by 2050.

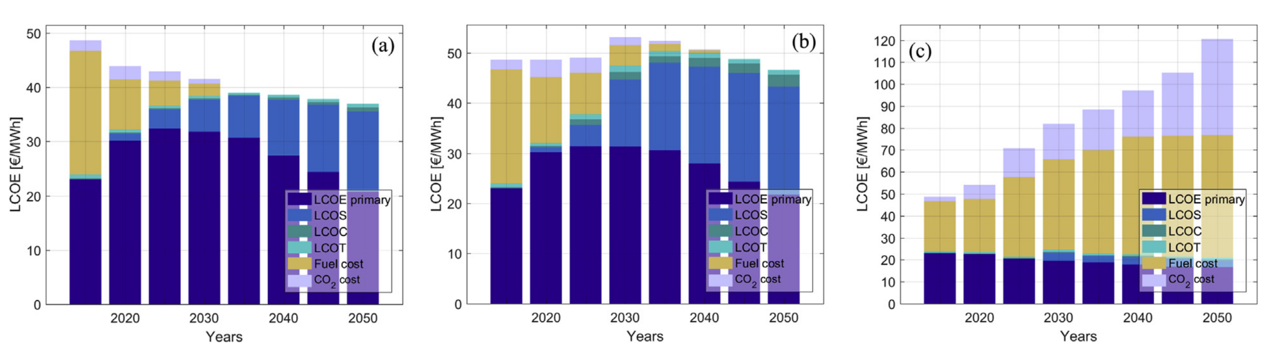

Fig. 15. Levelised cost of electricity in the BPS-1 (a), BPS-2 (b) and CPS (c) for 2050.

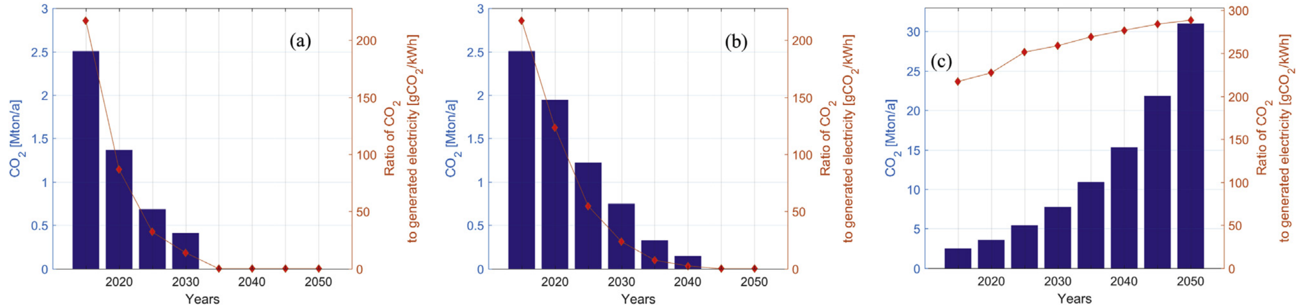

Fig. 16. The GHG emissions trajectory in the BPS-1 (a), BPS-2 (b) and CPS (c) during the transition period.

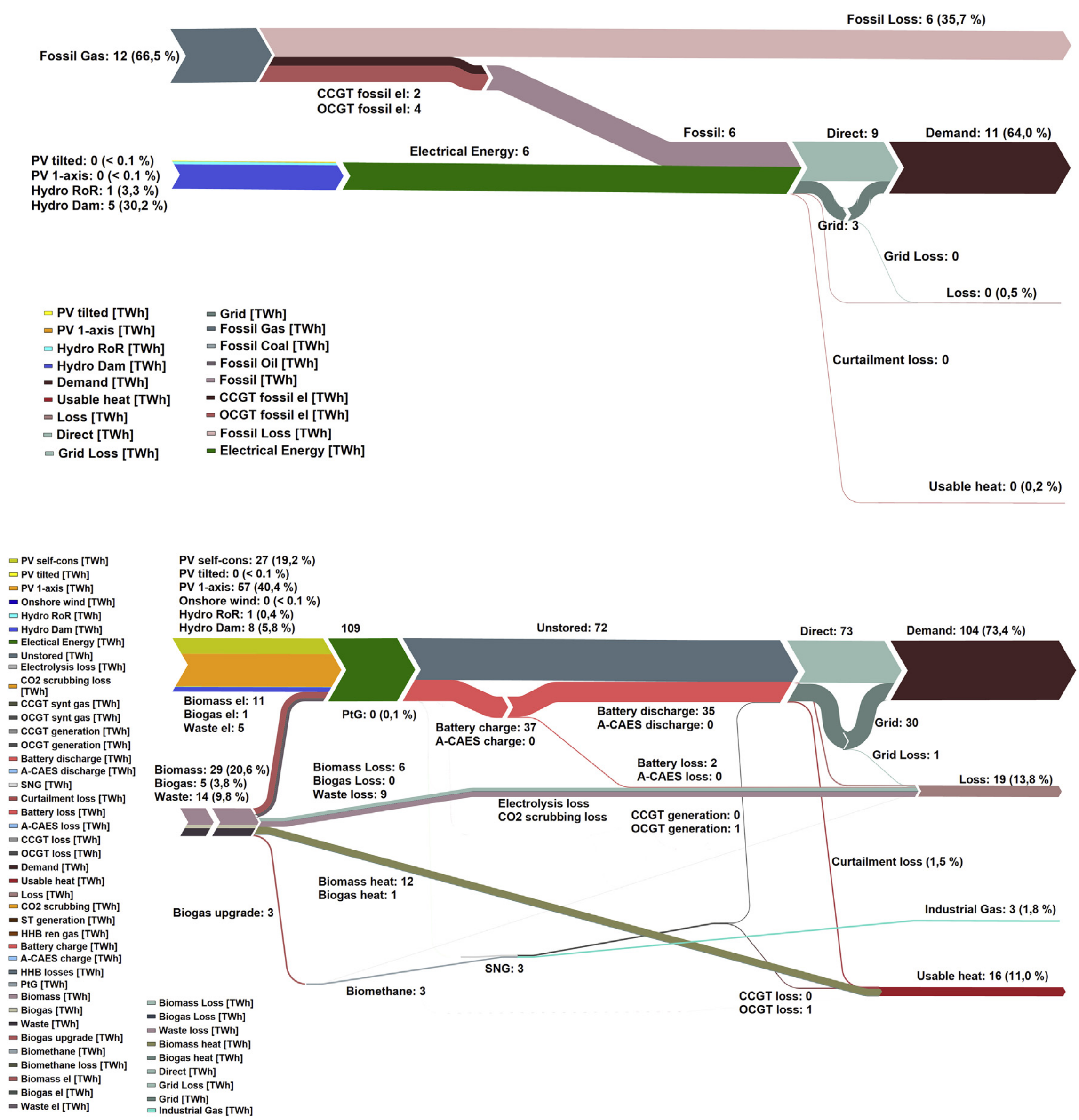

Fig. 17. Energy flow of the power sector for 2015 (top) and BPS-1 in 2050 (bottom).

the vital role of bioenergy is clearly seen as it augments the PV-battery hybrid energy system by providing flexibility to the system. Losses occur mainly in curtailed electricity, biomass power plants, waste-to-energy plants, PtG processes, and battery charging and discharging processes. Additional information on the energy flow in the scenarios BPS-2 and CPS is presented in the Supplementary Material (Figures A19-A20).

4. Discussion

This case study investigates the role of sustainable modern bioenergy and the integration of large shares of RE resources for the case of the Ghanaian power sector, as illustrated in the BPSs, in comparison to a system dominated by fossil fuelled technologies as depicted in the CPSs.

4.1. The significant role of sustainable bioenergy in RE-dominated systems

The results of this case study show that the sustainable bioenergy potential of Ghana as of 2015 is 48.3 TWh which generated electrical energy of 18 TWh by 2050 when applied to the LUT model as shown in Fig. 7. The research recognises that by 2050, the bioenergy potential of Ghana may alter due to changing climate conditions.

Solid biofuels and biogas are converted in CHP plants and gas turbines respectively, to provide short-term to mid-term and seasonal balancing of the RE resource dominated power sector. This role highlights the synergy between variable RE sources and modern bioenergy.

Bioenergy is a dispatchable form of RE generation and has the potential of providing a stabilising role in a power grid dominated by RE resources [6]. The results of this study revealed that most of the dispatchable renewable power needed in the BPS-2 is provided by hydropower and gas turbines. The missing bioenergy capacity in the BPS-2 is largely compensated by additional PV capacity as shown in Fig. 6. Whereas, in the BPS-1 dispatchable renewable power is provided mainly by bioenergy plants, followed by hydropower and gas turbines. The cumulative installed capacity requirement is lower in the BPS-1 than in the BPS-2, due to influence of bioenergy plants running on higher FLH. The LCOE is 37.0 €/MWh and 46.6 €/MWh for BPS-1 and BPS-2 respectively by 2050. The cumulative installed capacity, total generation, storage output, curtailment and LCOE dropped by 22%, 12%, 37%, 41.6% and 27% in the BPS-1 compared to the BPS-2, by 2050. The increased LCOE in the BPS-2 is mainly influenced by storage cost (LCOS) owing to high penetration of solar PV, leading to excess generation, which needs to be stored, used, or curtailed. Other contributing components are cost of curtailment (LCOC), and LCOE primary cost.

Curtailment costs are higher in the BPS-2 than in the BPS-1, due to high curtailment losses of about 10.1 TWh by 2050, as compared to 4.2 TWh by 2050 in the BPS-1. The high total curtailment losses in the BPS-2 can be attributed to excess generation from PV during low load periods, especially in the afternoon and balancing challenges due to the absence of bioenergy plants in the BPS-2. Variable RE generation and curtailment in the BPS-1, BPS-2 and CPS are shown in Fig. 18. Additional information on curtailment and generation for all scenarios are presented in the Supplementary Material (Figure A6).

Table 4
LCOE difference between BPS-1 and BPS-2 for 2050.

	Unit	BPS-1	BPS-2	Difference [%]
LCOE primary total	[€/MWh]	20.7	21.7	4.8
LCOC total	[€/MWh]	0.7	2.4	242.9
LCOS total	[€/MWh]	14.8	21.6	45.9
LCOT total	[€/MWh]	0.7	0.9	28.6
LCOE total	[€/MWh]	37.0	46.6	20.6

LCOE primary costs are equally higher in the BPS-2 than the BPS-1 since additional installed solar PV capacity is needed to compensate for the missing bioenergy capacity. About 15 GW of solar PV installed capacity is needed in the BPS-2 to compensate for the missing 4 GW of bioenergy installed capacity in the BPS-1. This is primarily due to the higher bioenergy plants FLH, the vast compensating installed capacity culminated in the higher final LCOE primary in the BPS-2. In addition, about 33.8 GWh_{cap} (29.4%) more battery storage capacity is needed in the BPS-2 compared to the BPS-1. Table 4 shows the LCOE difference between BPS-1 and BPS-2. The use of bioenergy improves the power system for a better primary electricity generation mix, less curtailment, less storage requirement, and slightly less power transmission requirement.

Power systems dominated by variable RE resources show the need for dispatchable technologies as demonstrated in BPS-2, which can be provided by bioenergy plants. The demand and supply of sustainable biomass for power generation to balance the energy system will create economic benefits, especially for the indigenous in the rural communities, where most residues are generated. Most importantly, the use of sustainable biomass will provide energy self-sufficiency (security of supply) and additional environmental and economic benefits [105]. The utilisation of Ghana's sustainable bioenergy for power production may limit the supply of biomass to other sectors of the energy system such as transport and heat (industry and cooking) even though some sustainability criteria have been considered for the bioenergy potential estimations. According to Refs. [25,106], although substantial energy demand by the transport and heat (industry, building and cooking) sectors will be supplied heavily by electricity, liquid fuel (PtL), and synthetic gas (PtG) in a fully sector coupling scenario, bioenergy may also be demanded by these sectors. Hence, the total bioenergy potential may not be available for the power sector in a fully sector coupling scenario. Thus, this study recognises this development as a limitation to the research work.

4.1.1. Important role of micro bioenergy conversion technologies

The various biomass resources listed in Table 1 can be converted via different processes such as direct combustion, gasification,

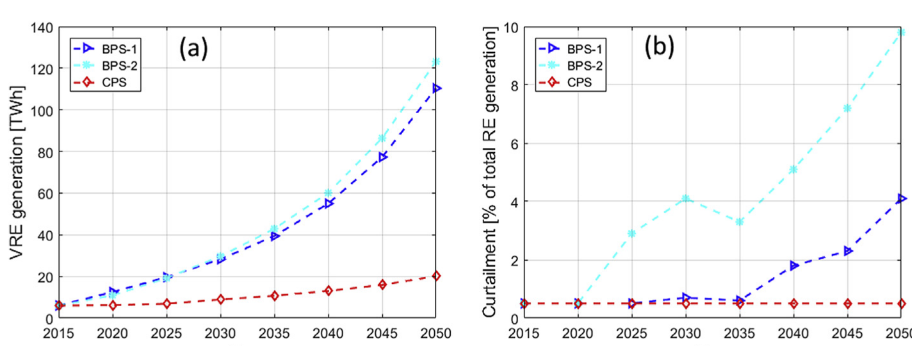

Fig. 18. Variable RE generation (a) and curtailment of generation potential (b) in TWh under various scenarios during the transition.

pyrolysis, extraction, fermentation, and anaerobic digestion to produce heat and power, ethanol, biodiesel, and biomethane [107]. This research however considered direct combustion and anaerobic digestion technologies for converting the available biomass into useful bioenergy.

4.1.2. Burning in dedicated power plants

Solid biomasses such as crop residues, forest residues, and wood residues could be burned to produce electricity via steam turbines in dedicated power plants. The produced electricity is consumed in the night or monsoon season. Currently, smaller sizes of about 100 MW or less are available in the market. Due to their ease of controllability, the CHP efficiently perform energy system balancing [6]. The CO_2 emissions of these plants are neutral since solid biofuels are biogenic. Municipal or district level MSW power plants are usually burned in a specially designed CHP plants due to their heterogeneous nature [107]. However, direct combustion of residue biomass for electricity production often results in the release of other air pollutant such as nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), sulphur dioxide (SO_2), and volatile air pollutants (VOC), But with proper boiler furnace temperature control, ash treatment, and flue gas treatment technology, these negative impacts could be overcome.

4.1.3. Anaerobic digestion plants

Wet and organic waste matter such as livestock manure, FSS, and organic kitchen waste could be converted by bacteria-induced fermentation into biogas of about 50%–75% methane, CO_2, and other impurities. Biogas produced via the anaerobic digestion process is upgraded into biomethane and subsequently fed into a national gas grid for firing the gas turbines for electricity production [107].

Ghana and other SSA countries with similar climate conditions could use this model for sustainable and reliable power production thereby addressing energy poverty challenge and ensuring economic empowerment of the locals. The application of this proposed model in Ghana and other SSA countries could provide benefits such as reduction of CO_2 emissions, energy supply security, affordability and adequate power, and most importantly economic growth [105].

4.2. The role of solar PV

The outstanding role of solar PV needs to be highlighted in the BPSs. Solar PV generates around 84–113 TWh representing 76–92% of the total electricity demand by 2050 in the BPSs. Utility-scale PV supplies 52%–70% of the electricity demand by 2050, and prosumer PV contributes around 22%–25% in the BPSs. Currently, the northern part of Ghana hosts the highest installed solar PV capacity and the first utility-scale PV in Ghana. The northern region of Ghana is expected to host more PV capacity in the future [108,109]. The plausible reason for the high share of solar PV installed capacity in the upper north in the BPS is due to high solar potential in this region [108] and the subsequent low cost. The results of this study show that solar PV emerges as the prime source of electricity supply for Ghana. These findings are comparable to that of Oyewo et al. [104] who concluded that solar PV will play a crucial role in the Nigerian future power system. Agyekum [109] analyses the benefit of solar PV systems for the Ghanaian power systems and confirms the results of this research, that single-axis tracking PV is the preferred utility-scale PV system for the conditions of Ghana. Similar insights have been obtained by studies for entire West Africa [5]. Barasa et al. [3] also conclude that most SSA countries can be powered majorly by solar PV and wind energy. The current trend of solar PV growth might be further accelerated due to continuously decreasing solar PV and battery cost [110] and the broader application of low-cost PV electricity in other energy sectors [111]. In the CPS, most of the electricity is supplied by gas turbines by 2050. Gas turbines dominate the total electricity generation with 87.1 TWh (81%), followed by solar PV with 9.8 TWh (9%), hydropower with 8.0 TWh (8%), wind energy with 1.4 TWh (1%) and biomass with 0.9 TWh (1%). It is worth mentioning that Ghana has enough land area to technically host a mix of RE-based system. The required land area for solar PV is calculated based on the capacity density assumed in the model, which is 75 MW/km^2 [98], which is conservative, given the steadily increasing PV module efficiencies. Thus, an area of 628 km^2 and 827 km^2 representing 0.26% and 0.35% of the Ghanaian total land area is need for solar PV capacities by 2050 in the BPS-1 and the BPS-2, respectively.

4.3. Analysis of system flexibility

The flexibility component of the power system includes storage technologies, the power transmission network, and dispatchable RE, particularly bioenergy resources (biogas, biomass, and waste) and hydropower. These flexibility components complement the high shares of solar PV in power generation as shown in Fig. 19. Power systems dominated by solar PV are often characterised by high storage requirement [82,112,113]. Storage technologies improve the system flexibility, particularly battery storage due to daily charge and discharge. Battery storage dominates in terms of storage output for all scenarios during the transition. Battery storage output is about 35 TWh (93% of all storage output and 34% of all demand) in BPS-1, 47 TWh (90% and 45%, respectively) in BPS-2, and 5 TWh (97% and 4.4% respectively) in the CPS. For weekly, seasonal, and long-term storage, TES, A-CAES and PtG are employed. Studies have shown that energy storage is needed in power generation with about 50% RE share [82], and the need for seasonal storage becomes apparent when RE share reaches 80% [82,112]. Instead, dispatchable RE generation, bioenergy resource and hydropower appear to be sufficient in providing the daily and seasonal balancing as shown in Fig. 19, during the monsoon period in BPS-1. As a result, only 0.08 GW of PtG capacity is required in the BPS-1 by 2050, whereas 1.7 GW of PtG is required in the BPS-2. This phenomenon is also observed for Brazil [114] and West Africa [5]. According to Refs. [5,112], a 100% RE-based power system can run with very low seasonal storage.

The power transmission grid network provides additional flexibility to the power system, particularly in balancing the spatial mismatch in generation and demand in the BPSs. The power grid facilitates the high shares of RE generation in the upper north, which are transmitted to other regions. Studies have shown the importance of transmission grid in power systems dominated by RE, which includes the potential to reduce LCOE and to facilitate high RE penetration [115]. Gas turbines appear to be relevant in the BPSs, particularly during the monsoon season. Studies have shown that gas turbines can provide flexibility in RE-based power systems, instead of coal or nuclear power plants [116].

4.4. Benefits of the energy transition

Most renewables have common economic characteristics: high fixed costs and low or almost no variable costs. Solar energy, wind energy, geothermal energy, tidal power, hydropower, and waste-to-energy conversion require substantial investment cost but no fuel cost. Their running costs include expenditures for maintenance and operations, and energy input in the case of waste-to-energy. Therefore, when a renewable power station is built, the operational costs of providing electricity to its users are low for the economic lifetime of the plant [117]. Recent plummeting prices for

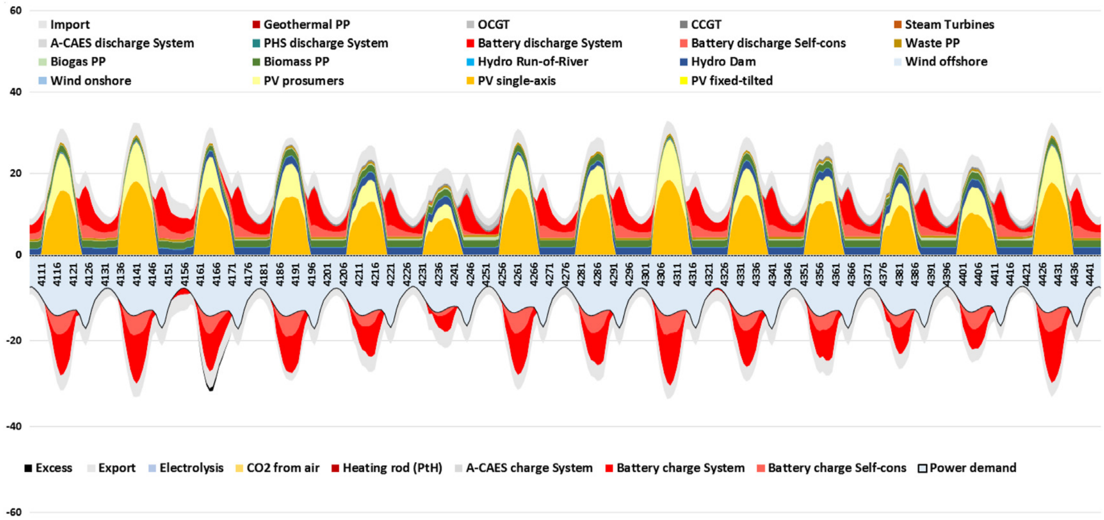

Fig. 19. Generation and demand profiles during the monsoon period in the BPS-1 for 2050.

Table 5
Key financial and technical parameters in 2050 for all scenarios.

		Unit	BPS-1	BPS-1noCC	BPS-2	BPS-2noCC	CPS	CPSnoCC
Financial outcome	Total annualised system cost	[b€]	3.87	3.86	4.84	4.77	12.79	8.11
	LCOE	[€/MWh$_{el}$]	36.97	36.89	46.6	45.96	120.55	76.42
parameters	Generation	[TWh$_{el}$]	110.35	110.37	123.2	119.5	107.42	107.4
	Installed capacity	[GW]	54.9	54.8	67.2	64.5	22.1	21.8
	Curtailment	[TWh$_{el}$]	4.21	4.29	10.12	9.98	0.53	0.53
	RE share	[%]	100	100	100	98.2	18.7	18.7

renewable technologies are influencing the capacity addition and driving more jobs in the installation, operation, and maintenance [118]. According to IRENA, the global GDP will increase by 1.1%, human well-being will be improved, as well as direct and indirect job could reach 24.4 million people by 2030, if the renewable share in the global energy mix is doubled [119].

According to the results of this study, it is empirically evident that increasing the share of renewable energy in the SSA generation mix will increase the regional GDP, reduce unemployment rates, and increase overall humane welfare due to the energy-economic growth nexus. The results, as shown in Table 5 depict that a 100% RE-based system is the least-cost option for Ghana. The LCOE obtained in the BPSs is around 37–46 €/MWh in 2050, which is comparable to the range of 35.2–47.6 €/MWh in Ref. [5]. According to Oyewo et al. [5], the Ghanaian power sector LCOE by 2050 will be in the range of 37.1 €/MWh and 46.5 €/MWh, when connected to the West African power pool and when isolated, respectively, which is similar to the results of this study. The total annualised cost of the energy system is in the range of 3.85 b€ to 12.79 b€, as presented in Table 5 for 2050.

The highest total annualised system cost occurred in the CPSs, which is 193% higher than in the BPSs with GHG emissions cost and is 88% higher without GHG emissions cost by 2050. On average, the required installed capacity in the BPSs is about 173% higher than the capacity requirement for the CPSs, due to RE technologies running on lower FLH, especially, solar PV in the BPSs. Additional information about total annualised cost can be found in the Supplementary Material (Figure A21).

Hybrid PV-battery systems used in tandem with modern biomass power appear to be the central and least-cost element for Ghana by 2050, which is comparable to the findings of Oyewo et al. [104] for the Nigerian and West African power system [5]. In addition, PV [103] and battery [120,121] costs have declined over the years, and further cost reduction is expected. The outcome of this research demonstrates the technical feasibility and economic viability of RE-based power systems in Ghana and SSA. Furthermore, the results of this study show that RE generation could reach 100% in BPS-1 and 98.2% in BPS-2 without GHG emissions cost, which indicates pure market economics, neglecting harmful impacts of conventional power generation, such as GHG emissions, but also heavy metal emissions.

The BPSs show that deep defossilisation of the Ghanaian power sector is not only cost-competitive, but also complies with the objectives of the Paris Agreement. The high costs observed in the CPSs is due to investments in thermal power plants, which run on high FLH and consumes enormous fuel, and which cannot compete anymore with low-cost PV-battery systems. The results of the CPSs show continuous dependence on gas turbines. Without GHG emissions cost, the BPSs show lower total annualised system cost, LCOE, and the installed capacity, as compared to the BPSs with GHG emissions cost. For the total annualised system cost, BPS-1noCC is lower than BPS-1 by 0.01 b€, BPS-2noCC is lower than BPS-2 by 0.07 b€. For the LCOE, BPS-1noCC is lower than BPS-1 by 0.08 €/MWh, BPS-2noCC is lower than BPS-2 by 0.064 €/MWh. For the installed capacity, BPS-1noCC is lower than BPS-1 by 0.1 GW, BPS-2noCC is also lower than BPS-2 by 2.7 GW. The minimal differences between the BPSs with and without GHG emissions cost are due to zero GHG emissions in RE resource power systems, but some deviations are induced during the energy transition. For the CPSs the differences are quite significant, the total annualised cost and LCOE are reduced by 4.7 b€ and 44.1 €/MWh from CPS to CPSnoCC. This shows the impact and influence of GHG emissions cost to the economics of the electricity market. The influence of GHG emissions cost is significantly observed between CPS and CPSnoCC, due to a high share of fossil-based technologies in the Ghanaian power generation mix. In short, GHG emissions cost does not significantly affect the LCOE of the power system with high RE resources, due to zero GHG emissions during the use phase.

The BPSs results show that Ghana can decarbonise its power sector, while reducing costs if the techno-economic analysis pathway options demonstrated in this research are pursued. It is the least-cost option for Ghana and does not require any form of subsidy. According to Ref. [122] countries such as Burkina Faso, Chile, China, Egypt, Ghana, India, Japan, Mexico, Namibia and Thailand are committed to using 100% renewable energy systems to help address the climate change crisis.

4.5. Off-grid electrification

Ghana is one of the top countries in Africa leading the progress in access to electricity. In Ghana, electrification access rose from 65% in 2010 to around 85% in 2019 [123–125]. However, majority of the population connected to the national grid are in the urban and peri-urban areas whiles rural electrification remains a barrier to Ghana's 2020 universal access target, which obviously is a mirage. About 15% of Ghana's population (4.6 million) living in less densely populated communities are not yet connected to the national grid [124]. Most of these people live in isolated locations far from the national grid, and grid extension to these isolated communities is costly and rather uneconomical [126]. Bertheau et al. [123] investigated the impacts of grid extension on electricity access in SSA, using a geospatial method, and the results indicate that for most isolated SSA rural communities which are sparsely populated, mini-grids and solar home systems (SHS) are the best solution for rural electrification. For Ghana, a scenario based on existing grid infrastructure indicates 12% SHS, 10% mini-grids and 78% grid extensions for the not yet electrified population. While another scenario assuming the planned grid indicates electrification of the not yet electrified people by 8% SHS, 8% mini-grids, and 84% grid extension to provide universal access to electricity in Ghana. Similarly, Sanchez et al. [127] conclude that, when it is too costly to build transmission lines due to distance, dispersion and maintenance issues, the use of decentralised generation is the preferred solution. Thus, off-grid solutions such as SHS and mini-grids provide a cost-effective and possibly very fast and feasible progress in rural areas for achieving universal access to electricity.

5. Conclusions and policy implications

Due to policy changes and improved market prospects, the global renewable electricity is expected to grow in the future [6]. The results of this study clearly indicate that bioenergy can provide a substantial share of the needed grid balancing required in a fully renewable power system. It is least-cost to supply electricity with RE resources by 2050, which requires continued efforts to ramp up respective capacities, starting now. Storage technologies, power transmission grid and dispatchable RE (bioenergy and hydropower) provide the system with required flexibility. Bioenergy appears to be an excellent dispatchable energy resource in a power grid dominated by solar PV, while reducing the total annualised system cost. New biomass framework conditions coupled with low feedstock prices and high CO_2 prices are needed to create a direct competition between biomass and fossil fuels. Given low prices and availability of feedstock, thermal biomass power plants could substitute fossil fuel fired power plants for the required power system balancing in a variable renewable dominated power system. However, the transport and the heat (industry, building and cooking) sectors demand for biomass may limit the availability of biomass for power production. Also, possible future constraints in biomass availability and economics due to climate change can discourage or restrict the investments in biopower technologies. Therefore, the current work can be further extended by investigating and projecting the future biomass availability in the region due to rapidly changing climate.

In addition, a 100% RE-based system can run with very low seasonal PtG storage, as seen in the BPS-1. The BPSs appear to be the least-cost options for the case of Ghana in comparison to the CPSs. The BPS without GHG emissions cost reaches 98.2% RE generation share, which indicates favourable market economics.

Policies to support RE resources integration in the power sector are very important. Likewise, policies to encourage sustainable biomass utilisation for electricity production, such as feed-in tariffs, capital subsidies, tax incentives, guaranteed market for bioelectricity among others are supportive. Beyond the technical and economic feasibility of a 100% RE-based system, strong political will and policy implementation is encouraged. Policies to limit new investments in fossil technologies are urgently needed to avoid costly and harmful stranded assets and RE development plans from a long-term perspective are required.

The results of this research on the case of Ghana have shown that: 1) A fully renewable power sector is both technically feasible and economically viable and also represents the least cost option in the long-term, when compared to a conventional power system. 2) A good synergy between PV-battery driven and dispatchable bioenergy. 3) Producing power from waste and residue biomass will provide a paradigm shift from traditional to modern biomass use, while improving waste management practices in SSA. 4) The scenario can be transferred to other SSA countries and Sun Belt regions of the world with similar climate conditions as Ghana.

CRediT authorship contribution statement

Theophilus Nii Odai Mensah: Data curation, Conceptualization, Writing – original draft, Methodology, (Bioenergy potential estimation). **Ayobami Solomon Oyewo:** Modelling, Visualization, Investigation. **Christian Breyer:** Supervision, Writing – review & editing.

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.

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Appendix A. Supplementary data

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