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THE ROLE OF MODERN BIOENERGY IN SOLAR PHOTOVOLTAIC DRIVEN AND DEFOSSILISED POWER SYSTEMS – THE CASE OF GHANA

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Supervisors: Professor Christian Breyer
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ABSTRACT

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The role of modern bioenergy in solar photovoltaic driven and defossilised power systems – The case of Ghana

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A mix of renewable and sustainable energy resources namely; solar photovoltaic, hydropower and biomass can achieve the entire defossilisation of the Ghanaian power sector. Storage technologies, transmission grid, hydropower and bioenergy resources furnish the needed flexibility to the system. A techno-economic analysis was performed with a cost optimisation-modelling tool. A comprehensive bioenergy potential assessment method was developed and applied for the case of Ghana, fully ascertaining the technically harvestable bioenergy potential. The case country Ghana is divided into six micro -regions and the optimisation is carried out in 5-year steps depending on technological and costs status, assumptions within the time horizon of 2015 to 2050, for all energy technologies involved. Six scenarios have been designed to study the energy transition options highlighting the role of bioenergy, greenhouse gas emissions costs, and highly ambitious climate mitigation policies. Hybrid of PV-battery systems surfaced to be the comparatively cheaper and prime technology in the ambitious Best Policy Scenarios. Levelised cost of electricity in the Best Policy Scenario declines from 48.7 €/MW in 2015 to 36.9 - 46.6 €/MWh in 2050, contrarily, by 2050, in the Current Policy Scenario without cost of greenhouse gas emission, electricity cost increased to 76.4 €/MWh. This study outcome clearly demonstrate that long-term low-cost power solutions are achievable through a wide variety of renewable energy technologies in the generation mix, supported the primarily by solar photovoltaics. The role of biomass power plants in the power system dominated by renewable energy resources was investigated and it was revealed that bioenergy has an essential role to play in stabilising a renewable power supply system.

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Theophilus Nii Odai Mensah
Lappeenranta 07.06. 2019.

Dedicated to my future wife.

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LIST OF SYMBOLS AND ABBREVIATIONS

BPS	Best Policy Scenario
CAPEX	capital expenditure
CCGT	combined cycle gas turbine
CPS	Current Policy Scenario
ECG	Electricity Company of Ghana
EC	Energy Commission
FAO	Food and Agriculture Organization
FLH	full load hours
GT	gas turbine
GRIDco	Ghana Grid Company
GNGC	Ghana Natural Gas Company
GAEC	Ghana Atomic Energy Commission
GHG	greenhouse gas
HVDC	high voltage direct current
IPP	independent power producers
IEA	International Energy Agency
LCOC	levelized cost of curtailment
LCOE	levelised cost of electricity
LCOS	levelised cost of storage
LCOT	levelised cost of transmission
LNG	liquified natural gas
LHV	lower heating value
MSW	municipal solid waste
MoE	Ministry of Energy
NPC	nuclear power center
NEDco	Northern Electricity Distribution Company
OCGT	open cycle gas turbine
OPEX	operational expenditure

PURC	Public Utilities Regulatory Commission
PV	photovoltaic
RE	renewable energy
RoR	run-of-river
RPR	residue to product ratio
SNG	synthetic natural gas
SSA	Sub-Saharan Africa
VRA	Volta River Authority
WACC	weighted average cost of capital
WAGP	West African Gas Pipeline

1. INTRODUCTION

Ghana is a sub-Saharan and Western African country located in the Sun Belt region with a population of 27 million, GSS and GHS (2014) in 2015, projected to be 50 million by 2050 (United Nations, 2015) and occupies a land area of 238,529 km^2. Energy poverty is a fundamental problem in the country, with an annual electricity consumption per capita of 350 kWh as compared to annual electricity consumption per capita of 3927 kWh and 15,250 kWh in China and Finland, respectively (World Bank, 2016a). The end users' electricity tariff as of 2017 was 0.154 € /kWh. The gross domestic product (GDP) per capita of the country has been rising annually by 4.4% from 2010 to 2017 (World Bank, 2016b), indicating a positive economic growth which needs the required energy impetus to facilitate and accelerate economic growth. Chen et al. (Chen et al. 2007) describe the direct impact of economic and population growth on electricity demand, implying that Ghana's electricity consumption per capita will increase substantially in the near future.

With an electricity access rate of 82.5% as of 2015, which has been increased by 2.6% annually from 1990 to 2015 (Kumi, 2017), Ghana appears to be doing well compared to neighbouring West African counties. However, the recent frequently occurring power outages and load shedding coupled with high electricity prices is a signal that energy insecurity is still a fundamental national challenge, which needs appropriate long-term sustainable solutions (Kumi, 2017; Energy Commission, 2018a). In order to address the intermittent power deficit that plagues the country, the government of Ghana through the Ghana Atomic Energy Commission (GAEC) and the Nuclear Power Centre (NPC) proposed a roadmap to add 1000 MW of nuclear power generation capacity to the energy mix, within a 14 year period, with 2015 as the reference year (Energy Commission, 2018b). In addition, the Volta River Authority (VRA) with the Shenzhen Energy Group (SEG) developed a plan to construct four 350 MW supercritical coal-fired power plants (VRA, 2017). However, the environmental challenges of coal power plants would not make it a suitable option for the Ghanaian government, taking into account the country's commitment to the Paris Agreement. Likewise, nuclear power plant capital expenditures are comparatively expensive (Ram et al. 2018; Child et al. 2019; Child et al.2016), in addition to further violation of sustainability limitations and guardrails (Brown et al. 2018; Child et al. 2018), making the nuclear option highly unlikely as it may incur additional national debt (Energy Commission, 2018b).

Renewable energy (RE) resources, which are now economically highly competitive to the conventional fossil fuels could be the alternative energy source to provide the much-needed decoupling between economic growth and greenhouse gas emissions, thereby ensuring sustainable economic development (Ram et al. 2018; IRENA, 2018a). Recent studies show that, the global weighted average levelised cost of electricity (LCOE) of utility-scale solar photovoltaic (PV) systems have been reduced by 68% within a period of seven years (2010 – 2017) (IRENA, 2018a; ITRPV, 2019). Examples for the new record low cost for solar PV on LCOE basis can be found all around the world in countries like Saudi Arabia, Abu Dhabi, Dubai, Chile, Mexico, Peru, and the US, all around 20 to 26 €/MWh (IRENA, 2018a; IEA, 2018.). Most studies indicate that Ghana has very good potentials to harness enough energy from RE sources, especially solar energy (UNEP, 2016) and biomass. Zero "use phase" greenhouse gas (GHG) emissions, besides low-cost energy, is the key driver for RE resources to solve the two biggest problems: firstly, the global challenge of mitigating climate change and secondly, the regional and local challenge of addressing energy poverty in developing and emerging countries. Studies show that in a region where the RE potential is abundant, total solar PV capacity is still comparably low at 64 MW by the end of 2018, according to IRENA (IRENA 2019) or even 144 MW end of 2017 according to (Werner et al. 2018), while energy poverty still plagues the region.

The government of Ghana has enacted the Renewable Energy Act, which targets 10 percent renewable generation in the country's generation portfolio by 2020 (IRENA, 2015; EC, 2011). However, current developments indicate that achieving this target by 2020 might not be possible due to low investments in renewable energy capacity in the country (Obeng-Darko, 2019). Ghana's installed power capacity is mainly thermal power plants and hydro-dams as shown in Figure 1.

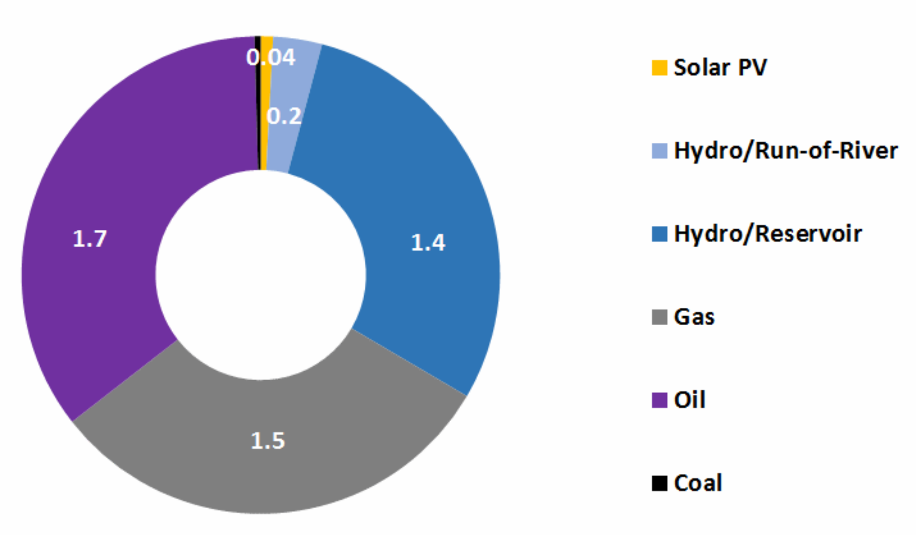

Figure 1. Installed power capacity in Ghana by 2017 in GW (Energy Commission, 2018a)

The current deregulated power sector consists of the Ministry of Energy (MoE), tasked to formulate and implement policies pertaining to the power sector (Eberhard, 2013). The Public Utilities Regulatory Commission (PURC) and the Ghana Energy Commission are responsible for the regulatory oversight of the power sector. Electricity generated by the Volta River Authority (VRA) and Independent Power Producers (IPP) are transmitted to bulk customers such as Electricity Company of Ghana (ECG) and Northern Electricity Distribution Company (NEDco) through Ghana grid company (Gridco). The ECG distributes electricity to the southern part of the country, while its counterpart the NEDco distributes electricity to the northern part of the country. Figure 2 shows the organisational structure of the Ghanaian power sector.

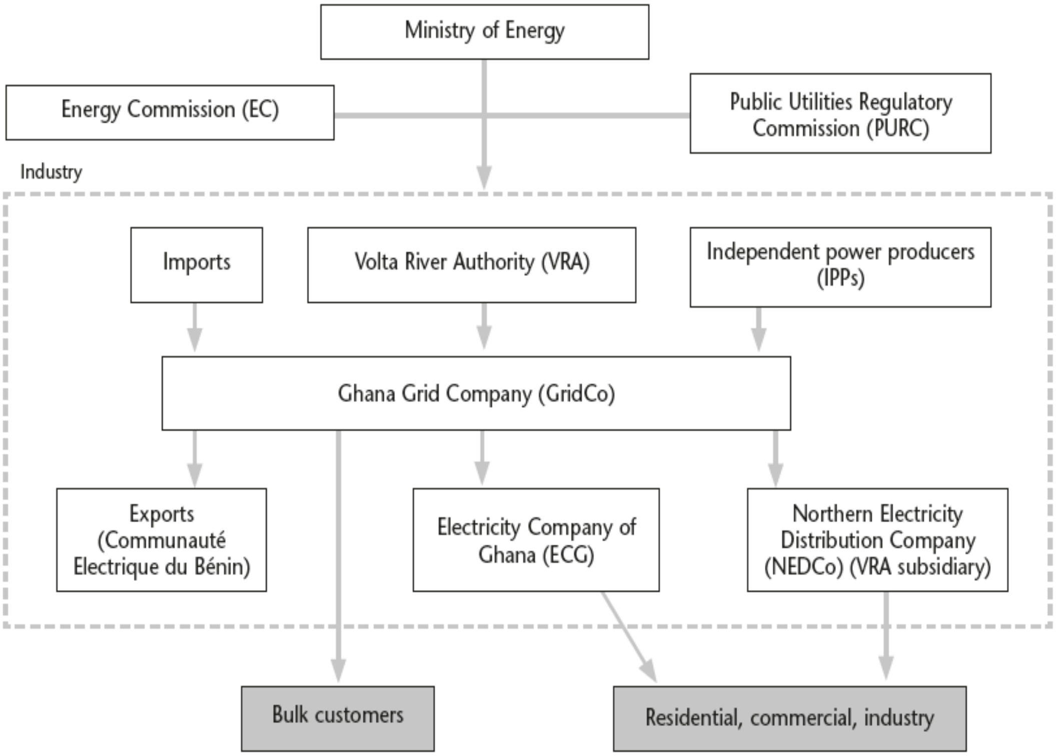

Figure 2. Ghanaian power sector overview (Eberhard 2013).

This research investigates the integration of large shares of RE resources into the Ghanaian power system under various policy constraints. Six scenarios were examined to better understand the least-cost pathway. Based on the government plans, a Current Policy Scenario (CPS) and proposed Best Policy Scenarios (BPSs); highly renewable and GHG emission free scenarios which fully meet the Paris Agreement requirements. Furthermore, Sun Belt countries of similar climates as Ghana have demonstrated hybrid PV-Battery systems as the dominant technology (Bogdanov et al. 2019), however, power systems with increasing contribution from variable RE sources face increasing flexibility requirements (IEA, 2019). For this reason, the role of bioenergy as a key source of flexibility is examined in the respective scenarios in this study.

The role of biomass in power systems dominated by RE resources and its balancing effect is investigated, particularly in the Best Policy Scenario. Currently, biomass electricity production in Ghana is at a nascent stage, despite the substantial bioenergy potential in the country (Energy Commission, 2018a). Bioenergy has the potential to balance power systems dominated by variable

RE (IEA, 2019). According to (Energy Commission, 2018c), there is no detailed scientific study to ascertain the bioenergy resource profile and characterisation for power generation in Ghana. To fill the knowledge gap, this research develops a comprehensive method for improved bioenergy potential assessment, based on international statistics. The obtained additional detailed estimation of technically harvestable bioenergy potential of Ghana is applied to the respective scenarios.

The modelling is carried out in 5-year steps based on cost assumptions and technology status up to the year 2050. This paper is organised as follows: section 2 outlines 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.

2. RESEARCH METHODS

The Ghanaian power system was modelled with the LUT Energy System Transition model described in (Bogdanov et al. 2019). The 16 administrative regions of Ghana are merged into six micro-regions forming six nodes in the model. The six micro-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 micro-regions are interconnected through a power transmission grid as depicted in Figure 3.

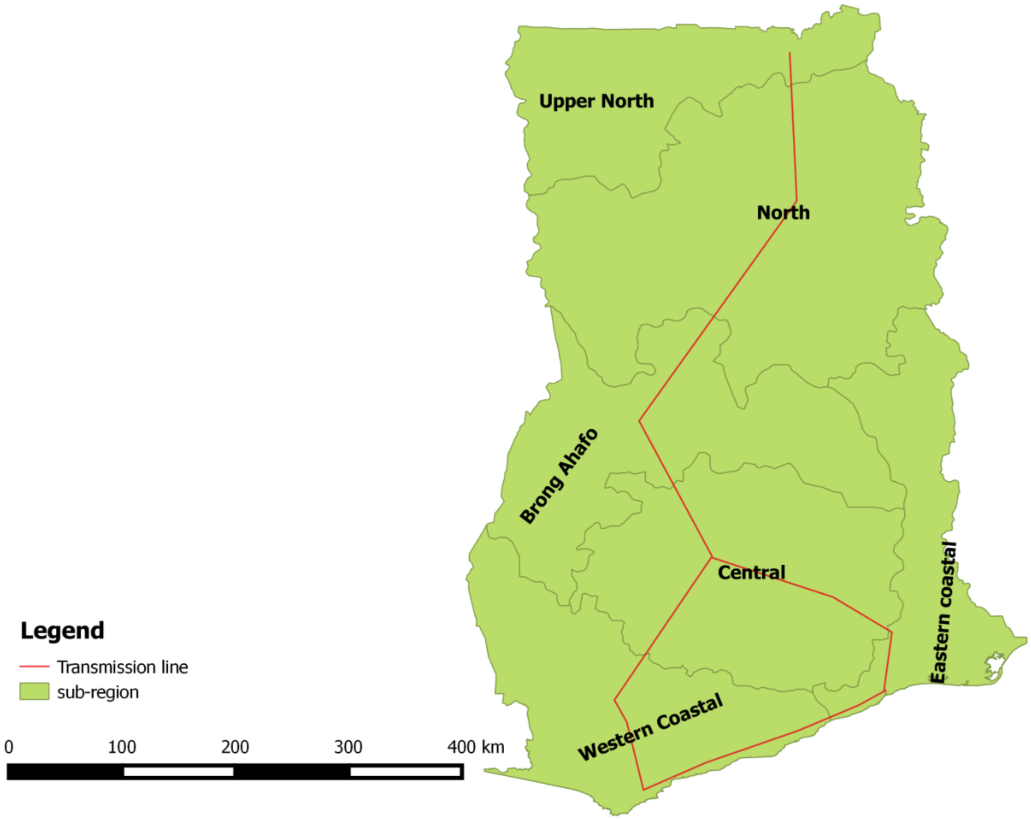

Figure 3. The six micro-regions of Ghana and power transmission grid configuration.

2.1 LUT Energy System Transition model overview

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. Figure 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. 2019).

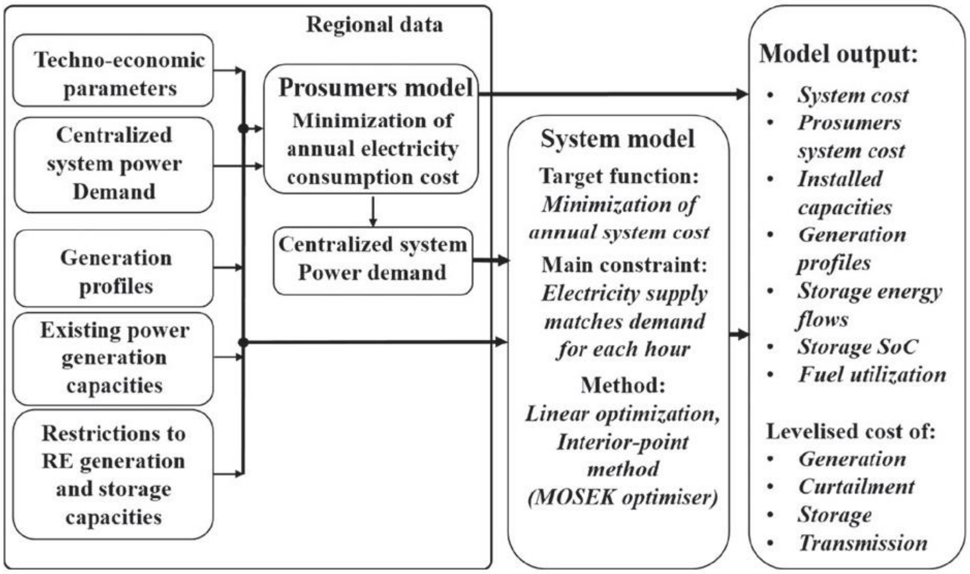

Figure 4. Flow diagram of the LUT model (Breyer et al. 2018).

In addition, the energy system planning includes residential, commercial and industrial PV prosumers, as studied in detail in (Keiner et al. 2019). 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 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 permitted to be installed after 2015 in the Best Policy Scenario. The current available fossil-based power plants are decommissioned as and when their economic lifetime expires. This excludes gas turbines. Gas turbine installation are allowed after 2015 owing to its lesser 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. As a means prevent system disruptions, the growth of RE capacity is restricted not to exceed 4% per year.
3. The prosumer demand is limited to 20% of the total demand; excess generation is allowed to be fed into the grid, but not more than 50% of total PV prosumer generation. The prosumer generation is constrained in a step-wise progression from a maximum of 6% in the initial time step to 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 Employed technologies

The main technologies applied for the Ghanaian power sector modelling includes electricity generation, power transmission, storage and energy bridging technologies. Existing transmission grid capacity was taken from West African Power Pool (WAPP, 2011), transmission and distribution grid losses were considered according to (Sadovskaia et al. 2019) and electricity load profiles were taken from (Toktarova et al. 2019). The storage solutions comprise battery, pumped hydro energy storage (PHES) (Ghorbani et al. 2019), adiabatic compressed air energy storage (A-CAES) (Aghahosseini et al. 2018), and power-to-gas (PtG) storage (Gotz et al. 2016), including electrolysers, CO_2 direct air capture (Fasihi et al. 2019), methanation and gas turbines. Figure 5 depicts the block diagram for the energy transition model.

Table 1. Transmission and distribution losses in percentage.

2015	2020	2025	2030	2035	2040	2045	2050
23,23	21,00	18,86	16,36	13,30	10,87	9,54	8,88

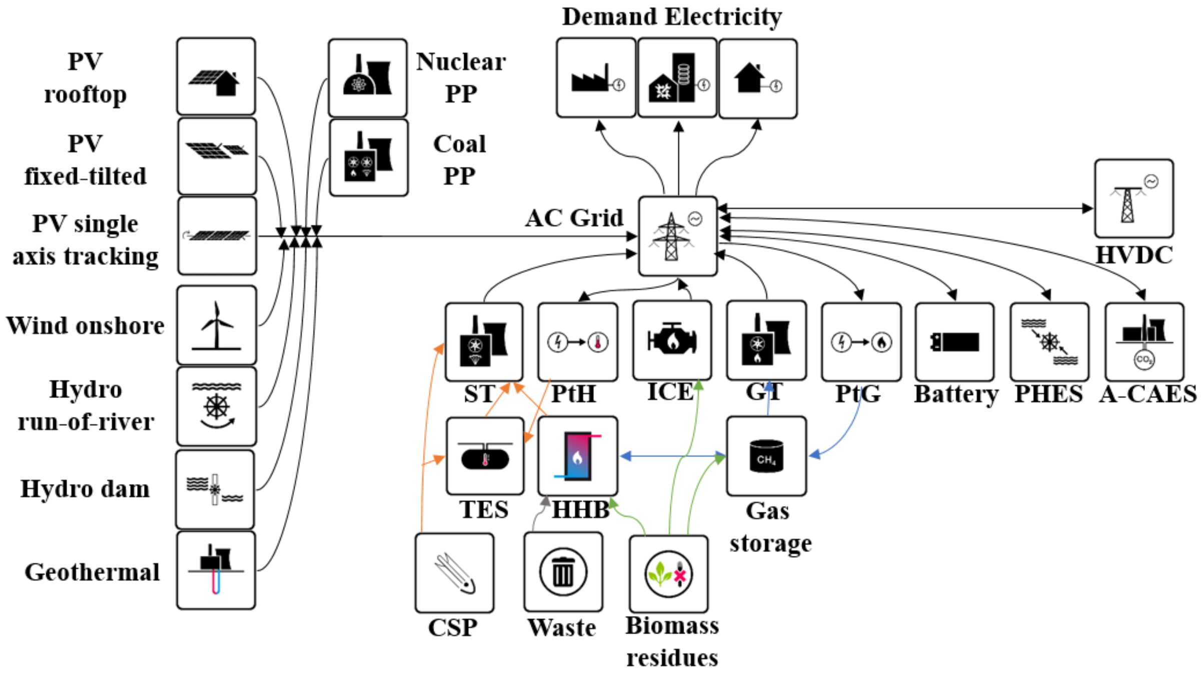

Figure 5. Block diagram of the LUT Energy System Transition model for the power sector (Breyer et al. 2018).

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, ICE, internal combustion engine.

2.3 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 namely; hydro, solar, biomass and wind. Wave, geothermal and tidal are not considered.

2.3.1 Solar, Wind, and hydro Potential.

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 (Breyer et al. 2018) and (Afanasyeva et al. 2018), based on resource data from NASA (Stackhouse and Whitlock, 2008; 2009), reprocessed by the German Aerospace Centre (Stetter, 2012).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 (Verzano, 2009). Additional information on full load hours for various recourses are provided in the Supplementary Material in Appendix (Tables A1-A6 and Figure A1) and generation profiles in (Figure A2). Figure 6 shows the resource maps for solar PV single-axis tracking and onshore wind energy for Ghana.

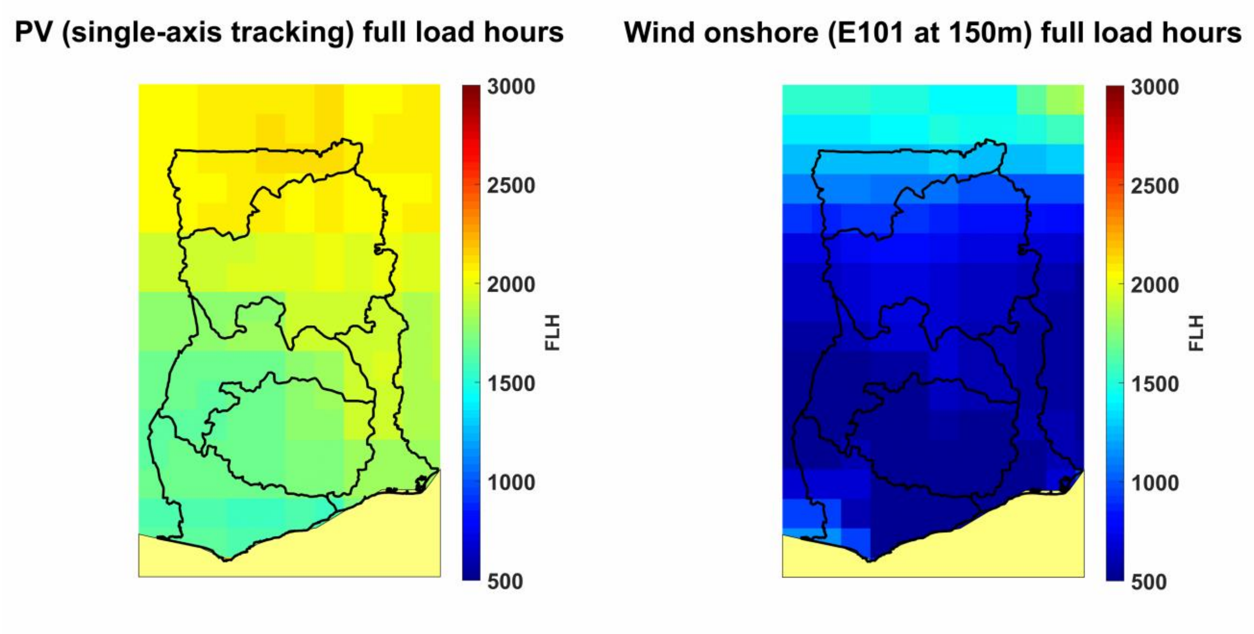

Figure 6. Full load hours per annum for onshore wind (right) and solar PV single-axis tracking (left) for the year 2050 for Ghana.

2.3.2 Bioenergy Potential Estimation

This sub-section presents a newly developed method for bioenergy potential estimation which is then applied for the case of Ghana. Energy derived from biomass is called bioenergy (USDE and USDA, 2005). Ghana is endowed with biomass resources, which includes agricultural crops and crop residues, wood and wood waste, municipal solid waste (MSW), animal waste, algae, sewage sludge, and aquatic plants (Forestry commission, 2013; Duku et al. 2011). Only residues are considered for the bioenergy potential estimation. Residues include wood residues, crop residues, sewage sludge, animal manure, and municipal solid waste. Algae and aquatic plants are not considered.

Energy from crop residues is calculated based on FAO data (FAOSTAT, 2015a) for the Ghanaian crop production for the year 2015. The residue to product ratio (RPR), (IEA, 2010) 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 from (Koopmans et al. 1997). It is assumed that the availability or use factor for residues is 35% (FAO, 2014) 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 crop residue energy potential per annum, (*CP)* is crop production for the reference year 2015, (*RPR)* is the residue to product ratio of a particular 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.

Annual bioenergy potential from wood residue 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 total fuel energy per annum harnessed from forest residue, *(WP)* is the total wood production for the reference year (FAOSTAT, 2015b) (*RPR)* is the residue to product ratio of a particular wood type and (*n*) represents the total number of wood types considered. (*LHV)* is the lower heating value of specific wood residue (Mitchual et al. 2014) and *(fuse)* is the use factor.

Animal manure potential for bioenergy is accounted on manure per head of livestock per annum (Barker et al. 2012) and applied for the case of Ghana based on FAO (FAOSTAT, 2015c) data on livestock for a reference year. The use factor for animal manure is assumed to be 80% for the case of Ghana. Sewage sludge is estimated based on population data and specific faeces per person per annum. Respective data for Ghana is extracted from (Colón et al. 2015). Bio-waste (kitchen waste) is estimated by population and generation per capita per annum (Miezah et al. 2015)

Annual animal manure, biowaste and sewage sludge is estimated according to Eqs. (3), (4), and (5).

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

$$S_s = (P_h \cdot H_f \cdot fuse) \tag{1}$$

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

Where (M_a) is the manure produced per annum, (P_a) is the animal population per annum, (M) is the manure per head per annum in tonnes, (n) is the different types of livestock considered, and ($fuse$) is the use factor of 80% for Ghana. (S_s) is sewage sludge 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 bio-waste (kitchen waste), (W_{bio}) is the bio-waste generation per person, (P_h) is the human population. The total feed stock for the anaerobic digestion, which includes; animal manure, biowaste and sewage sludge is estimated according to Eqs. (6).

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

Where (F_i) is the total feedstock, (M_a) is the manure produced per annum, (S_s) is sewage sludge per annum, and (Q_{bw}) is the bio-waste (kitchen waste).

Animal manure, sewage sludge, and organic bio-waste (food and garden waste) is treated with anaerobic digestion to yield biogas as a final product. Equation (5) is used to estimate the energy content of biogas produced from animal waste, sewage sludge, and organic bio-waste.

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

Where (E_{BG}) is the estimated annual biogas energy from the above-mentioned feedstock. (F_i) is the feedstock, which includes manure, sewage sludge, and bio-waste. (T_s) is the total solid share of the feedstock, factored in as a percentage value. (Vs) is the volatile solid share of the feedstock.

(Bio_{vs}) is the biogas yield per volatile solid of a specific feedstock. (C_{CH4}) is the methane content of a specific biogas feedstock. (LHV_{CH4}) is the lower heating value of methane (Steffen et al. 1998; SGTC, 2015).

Municipal solid waste per capita is obtained for the case of Ghana from (Miezah et al. 2015). Municipal solid waste 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 converted in an anaerobic digestion process described in Eq (5). Since the focus is on renewables, only the biogenic share of the MSWis considered. Biogenic part of the municipal solid waste is the fraction of the municipal solid waste which is considered to be biomass originated and therefore, considered as renewable. Examples of such fraction includes paper and cardboard, pampers, textiles from plants, rubber from plants, used wood, paper packaging, and leather (EIA, 2007). The energy potential of MSW is estimated according to Eq. (6).

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

Where (E_{MSW}) is the total annual energy potential of MSW. (Q_{MSW}) is the waste generation per capita per annum, excluding bio-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 (EIA, 2007; WB, 2012), and (LHV_{MSW}) is the lower heating value of mixed waste fractions (Scarlet et al. 2015).

The main contributors and sub-contributors of crop residue, forest residue, manure, sewage sludge, bio-waste, and municipal solid waste for the biomass potential of Ghana are presented in the Table 2 below.

Table 2. 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	Sawn wood, coniferous	Sewage sludge	Miscellaneous
7	Sweet potatoes	Sawn wood, non-coniferous	Bio-waste	
8	Groundnuts	Veneer sheets		
9	Yam	Plywood		
10	Banana	Particle board		
11	Plantain			
12	Coconut			
13	Oil palm fruit			
14	Coffee			
15	Cocoa			
16	Cassava			
17	Maize			

The total bioenergy harnessed from crop residue, forest residue, manure, sewage sludge, biowaste, and municipal solid waste is calculated with Eg. (7).

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

Additional information on Ghana’s bioenergy potential is provided in the Supplementary Material in Appendix (Tables A7-A13).

2.4 Technical and Financial Assumptions

The technical and financial assumptions for all the technologies used in the energy system, as well as components, and sub-components are made in 5 year time intervals and is provided in the Supplementary Material in Appendix (Table A14). This includes the capital expenditure (CAPEX), operational expenditure (OPEX), and lifetimes 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 provided in Supplementary Material in Appendix in Appendix (Table A15-A17). The average end-users electricity prices for commercial, residential, and industrial for the base year 2015 were obtained from Public Utilities Regulatory Commission (PURC) of Ghana (PURC, 2018). The electricity prices were calculated until 2050 based on (Breyer et al. 2013; Gerlach et al. 2014). Electricity prices applied are provided in Supplementary Material in Appendix (Table A18).

The RE upper limits were calculated based on Bogdanov and Breyer (2016) and lower limits were retrieved from Farfan and Breyer (2017). Resource potential for bioenergy is estimated according to the introduced method already described in section 2.3.2.

2.5 Projected electricity Demand

The electricity demand for Ghana is projected based on IEA demand growth rate for West Africa obtained from (IEA, 2014). The electricity demand projection until 2050 can be found in the Supplementary Material in Appendix (Table A18). The hourly load profile is estimated according to (Toktarova et al. 2019) and shown in Figure 7.

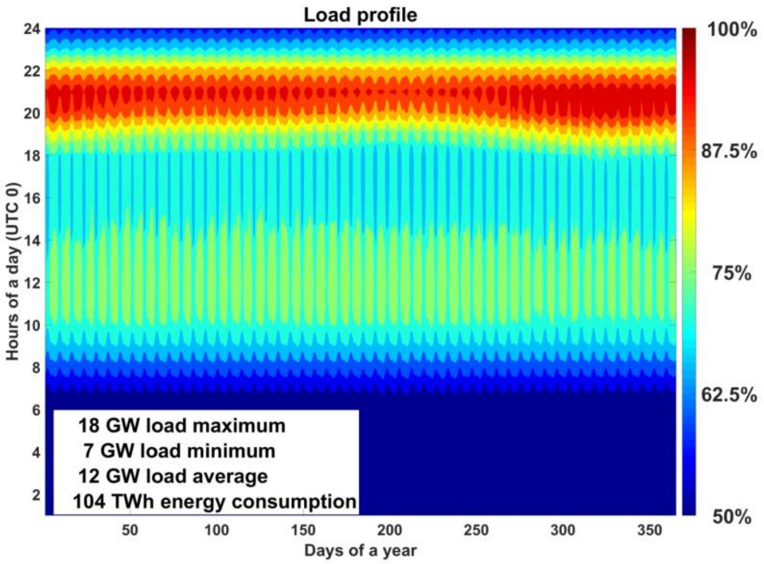

Figure 7 shows the hourly load profile.

2.6 Alternative Scenarios

Six energy scenarios were developed in this study as described in Table 3. The principal objective is to run a Best Policy Scenario (BPS) with bioenergy and the same without bioenergy to investigate the effects and significance of dispatchable bioenergy for balancing energy systems 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 well it could be utilised to serve the national grid, than just for heating and cooking purposes, as is the practice currently in Ghana and other African countries, a practice termed as traditional biomass (IRENA and DBFZ 2013). It is reported by (IEA, 2016a), that less efficient and unsustainable traditional biomass and solid waste contributes about 38.5% 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 (Energy Commission, 2018b) 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.

Table 3. 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-2noCC)	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 (Energy Commission, 2018b). Subsequent years after 2030 to 2050 are extrapolated accordingly.
Current Policy Scenario without GHG emission cost (CPSnoCC)	Current Policy Scenario without GHG emission cost.

3. MODELLING RESULTS

In this chapter, the main outcome of this research is presented. Results of scenarios with no GHG emission cost are not presented in this section due to similarities with scenarios with GHG emission cost. However, key parameters and financial results differences for various scenarios are discussed in section 4.4.

3.1 Estimated bioenergy potential of Ghana

The results of the bioenergy estimation for crop residue, forest residue, manure, food, sewage sludge, and municipal solid waste is presented in the Table 4.

Table 4. Ghanaian bioenergy potential in the year 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

The energy potential harnessed from the various feedstocks varies annually due to the variations of some key parameters such as human population, animal population, annual crop production, annual forest production, and municipal solid waste generation per annum. The crop residue category could be increased per annum if the farming efficiency of the country is increased.

3.2 Electricity installed capacity

Investments in the Ghanaian power sector are required to meet the future energy demand. Figure 8 presents the installed capacities during the transition period. Figure 8 (a)-(b) illustrates the installed capacities in the BPSs. The result indicates the dominance of solar PV during the transition. Solar photovoltaics contributes 47 GW (85%) in BPS-1 and 62 GW (93%) in BPS-2 by 2050. Asides solar PV, bioenergy, hydropower and gas turbines are included in the generation mix. Figure 8c illustrates the capacities development in the CPS. In the CPS, gas turbines and hydropower dominate the power system until 2030. Solar PV and wind energy capacity 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 are provided in Supplementary Material in Appendix (Tables A19-A24).

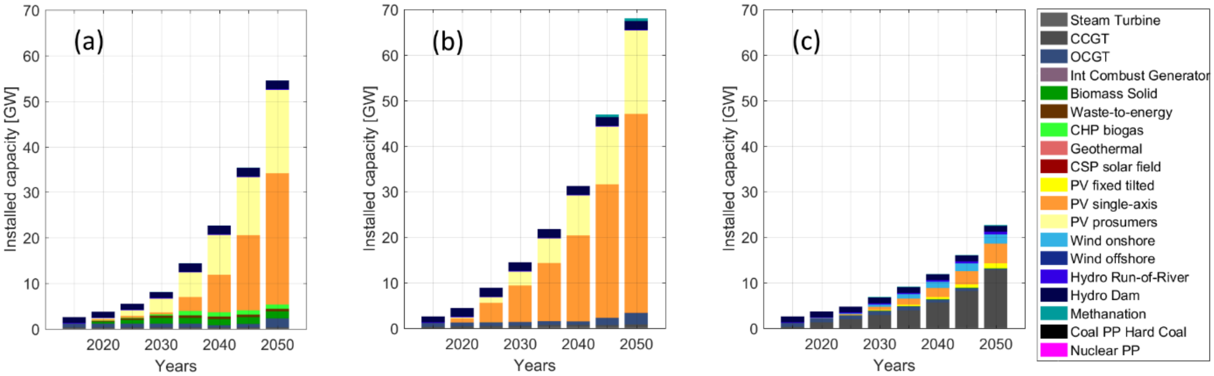

Figure 8. Cumulative installed capacities in the BPS-1 (a), BPS-2 (b) and CPS (c) for the years 2015 to 2050.

Figure 9 (a)-(b) depicts the electricity generation mix in the BPSs. By the year 2050, solar PV emerge as the dominating technology supplying electricity of 84 TWh (76%), followed by bioenergy with 18 TWh (15%) and hydropower with 9 TWh (8%) in BPS-1, whereas in BPS-2, solar PV dominates with 113 TWh (92%) and hydropower 9 TWh (7%). Figure 9c 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 provided in the Supplementary Material in Appendix (Figure A3).

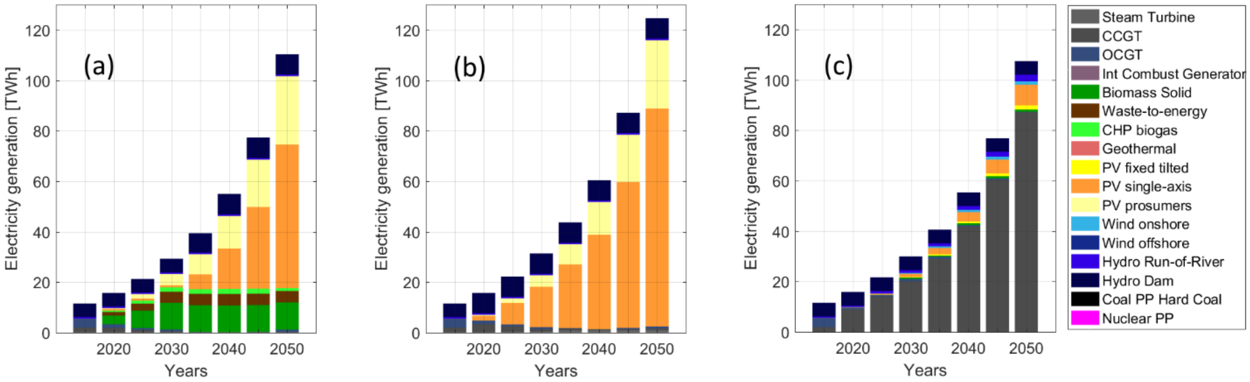

Figure 9. Electricity generation mix by different technologies in the BPS-1 (a), BPS-2 (b) and CPS (c) for the years 2015 to 2050.

3.3 Role of storage technologies

The role of storage increases with the shares of variable RE during the transition. Figure 10 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 32050 as shown in Figure 10a. In BPS-2 utility-scale battery dominate total storage output, followed by prosumer battery, TES and gas storage by 2050 as shown in Figure 10b. 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 Figure 10c.

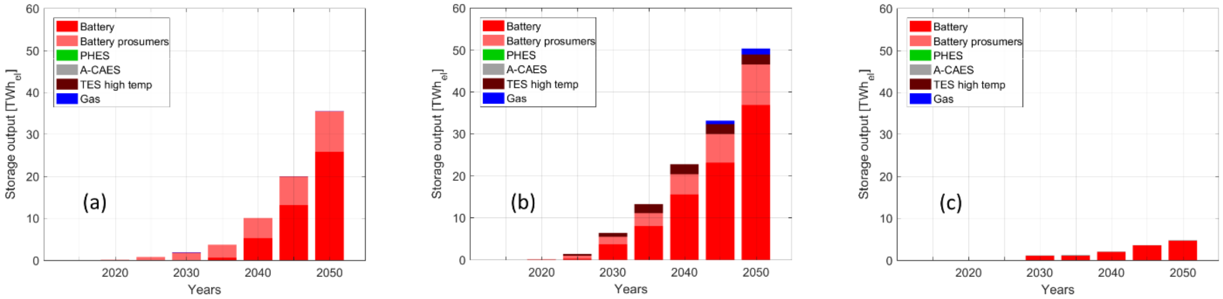

Figure 10. Output of storage technologies in the BPS-1 (a), BPS-2 (b) and CPS (c) for the years 2015 to 2050.

Storage capacity during the transition period in all scenarios considered is dominated by gas storage, particularly in the BPSs from 2045 until 2050 as depicted in Figure 11. Due to seasonal balancing, BPSs required higher share of gas storage. The significance of storage technologies emerged to be stronger in the BPSs than in the CPS, towing to high shares of RE in the BPSs.

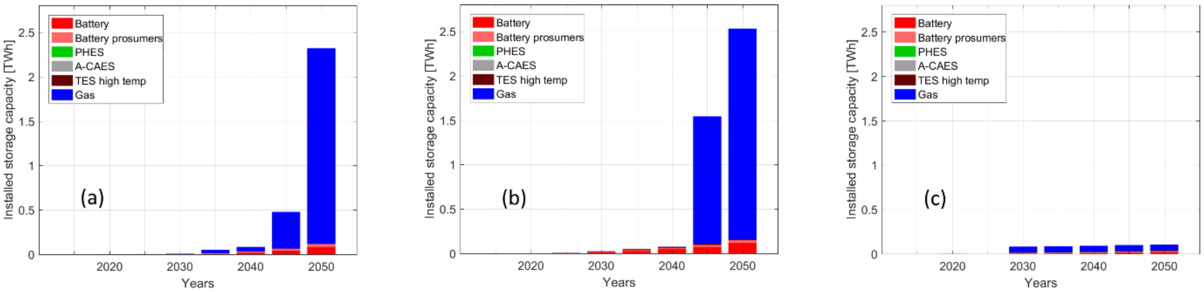

Figure 11. Storage capacity installation in the BPS-1 (a), BPS-2 (b) and CPS (c) for the years 2015 to 2050.

The battery-to-PtG effect (Gulagi et al. 2018; Oyewo et al. 2018), can be observed 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 utilization of electrolysers in off-peak hours, as demonstrated in the BPS-2 and depicted in Figure 12. In order to reduce total curtailment and PtG charging capacities, while maximising PtG FLH, which in effect reduces total energy system cost, battery is used to power the methanation process during low demand hours to produce synthetic natural gas (SNG) for long-term storage. Not discharged 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. Additional information on curtailment can be found in the Supplementary Material in Appendix in Appendix (Figure A4). The discharged battery is recharged during the day when solar PV production is high. The transferred electricity 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 provided in the Supplementary Material in Appendix (Figures A5-A7).

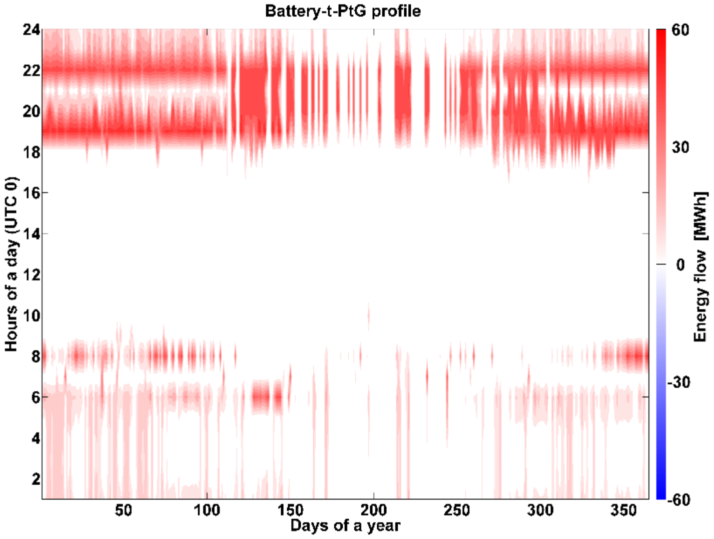

Figure 12. Profile of battery discharge to PtG in the BPS-2 by 2050.

3.4 Electricity grid utilisation

Grid interconnections provide further flexibility to the power system. The grid structure in the BPS is the opposite of the CPS. Figure 13 shows the electricity exchange in the BPS-1 and CPS. In the BPS, 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. Electricity exchange in the BPS is shown in Figure 13 (top) and comprises about 29 TWh (77% of local generation) of exports from GH-UN in the BPS by 2050. GH-UN is the main power production hub of Ghana in a fully RE power system. Whereas in the CPS, GH-EC and GH-CN emerge as the main exporting regions as shown in Figure 13 (bottom). The net grid transfer in the BPS is 30 TWh, representing 28% of the total electricity demand, compared to 20 TWh representing 18% in the CPS. Additional information on grid utilisation profiles is provided in the Supplementary Material in Appendix (Figure A8).

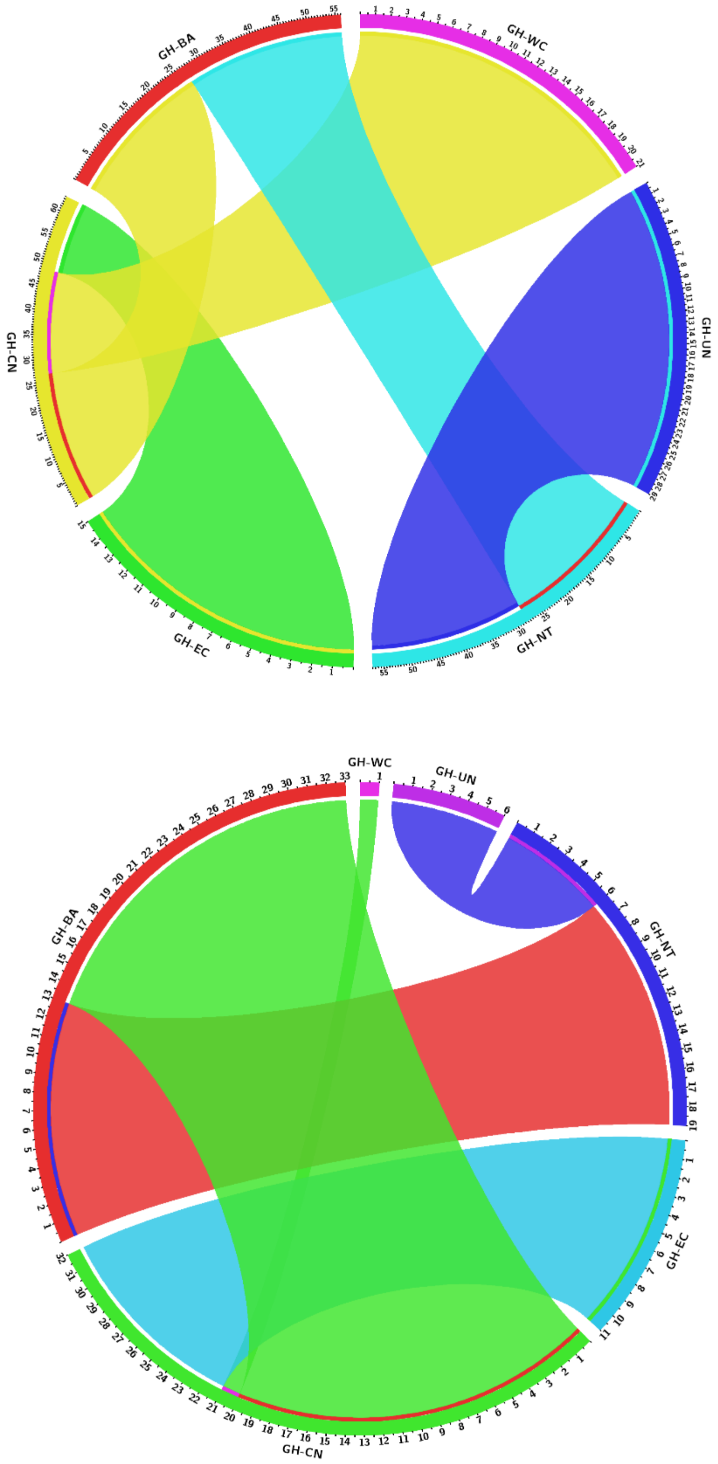

Figure 13. Power exchange across the country in the BPS-1 (top) and CPS (bottom) by 2050.

3.5 Role of gas turbines

The significance flexibility of gas turbines are due to their ability to cover a large time scale of frequency variation. Gas turbines are an ideal technology for balancing in the energy transition period towards 100% renewables. In the BPSs, gas turbines are permitted in the generation portfolio after the 2015 reference year, owing to less GHG emissions and high probability to replace natural gas with SNG and bio methane. The generation profiles of gas turbines (OCGT and CCGT) in the BPS and CPS are illustrated in Figure 14. 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 the West African monsoon season, which is most severe 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. Figure 15 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. Charge of the storage is during the year for peak discharge during the monsoon period.

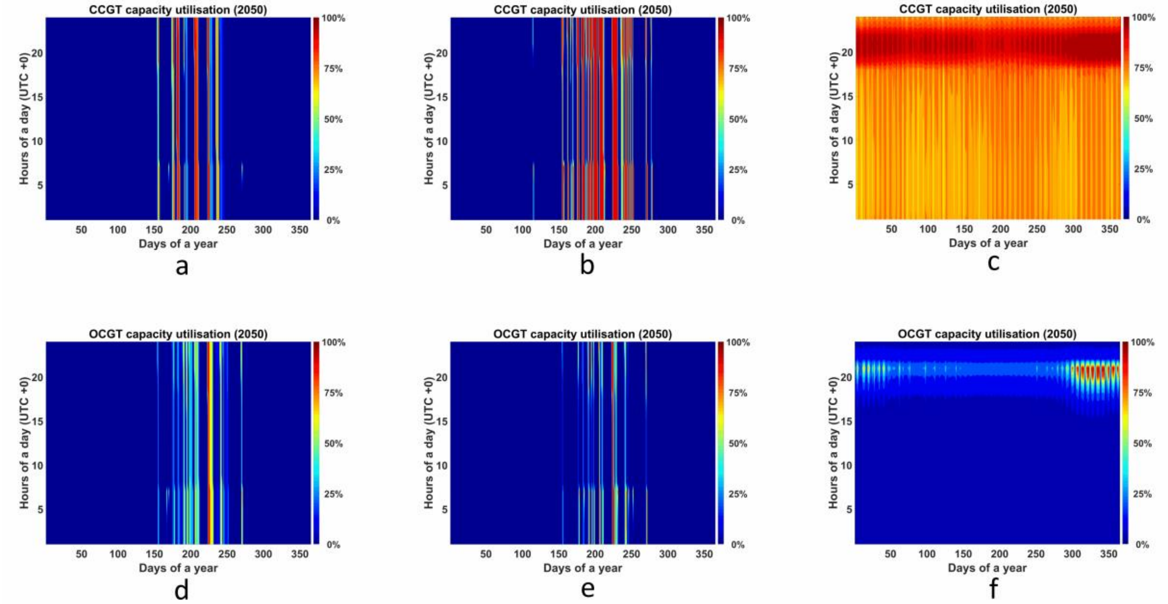

Figure 14. Combined cycle gas turbine profiles in the BPS-1 (a), BPS-2 (b), and CPS (c); and open cycle gas turbine profiles in the BPS-1 (d), BPS-2 (e) and CPS (f) in 2050.

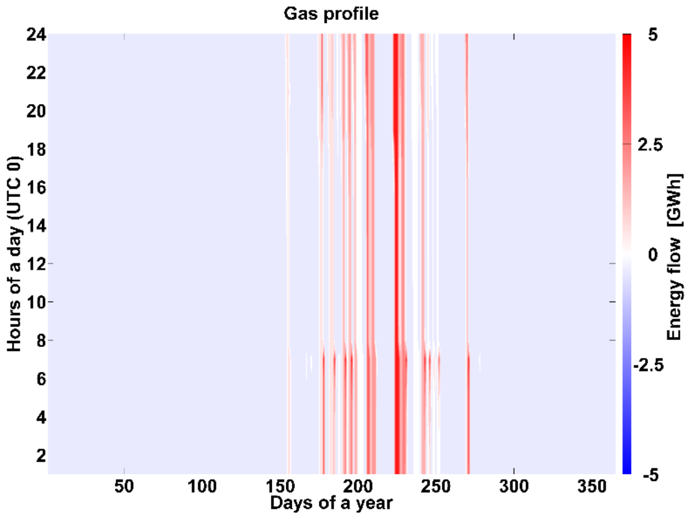

Figure 15. Gas storage profile during an entire year in the BPS-1 for 2050.

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

Figure 16 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 Figure 16a and 16b 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 regional installed capacities and generation is provided in the Supplementary Material in Appendix (Figures A9-A12).

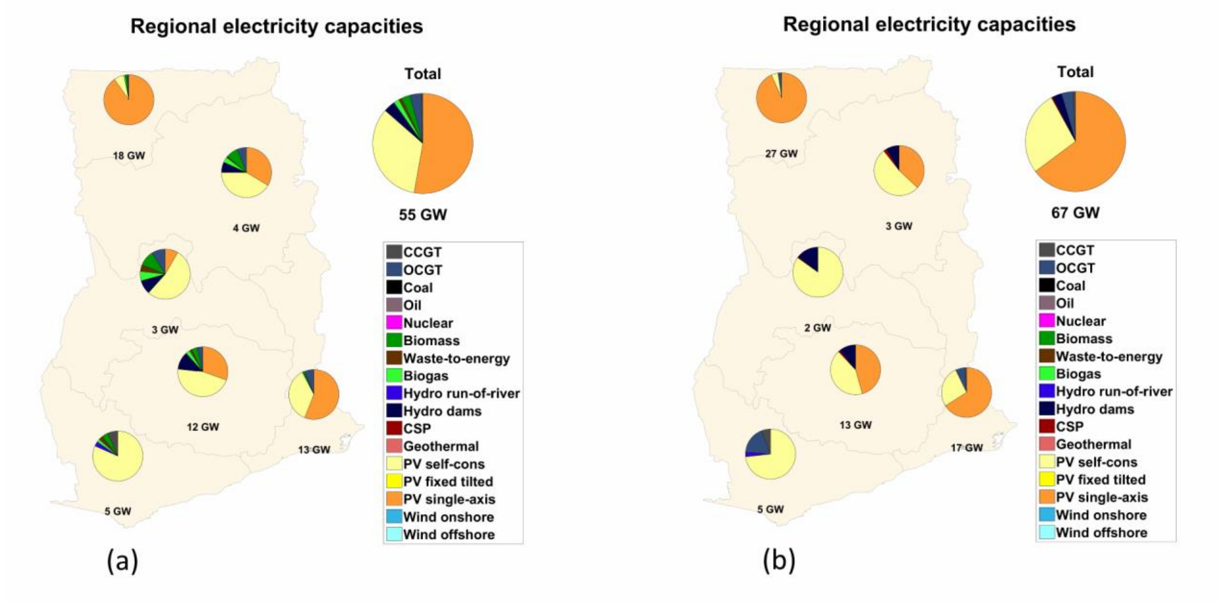

Figure 16. Sub-regional RE installed capacities for the BPS-1 (a) and BPS-2 (b) by 2050.

3.7 Levelised Cost of Electricity

The main contributors to the total energy system LCOE can be seen in Figure 16 (a)-(b) and (c). The LCOE includes the cost for generation, transmission, GHG emissions, storage, curtailment, and fuel cost. Figure 17 (a)-(b) show the LCOE in the BPSs during the transition period. The LCOE declines significantly from 48.7 €/MWh in year 2015 to 37.0 €/MWh in the BPS-1 and 46.6 €/MWh in the BPS-2 by 2050. In the CPS, LCOE increases from 48.67 €/MWh to 120.5 €/MWh as shown in Figure 17c. Contributing components such as fuel cost and GHG emissions cost starts declining from 2015 and finally diminishes at 2050, in the BPSs. However, storage cost starts to increase significantly from 2030 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 various scenarios are provided in the Supplementary Material in Appendix (Table A25 and Figures A13-A16).

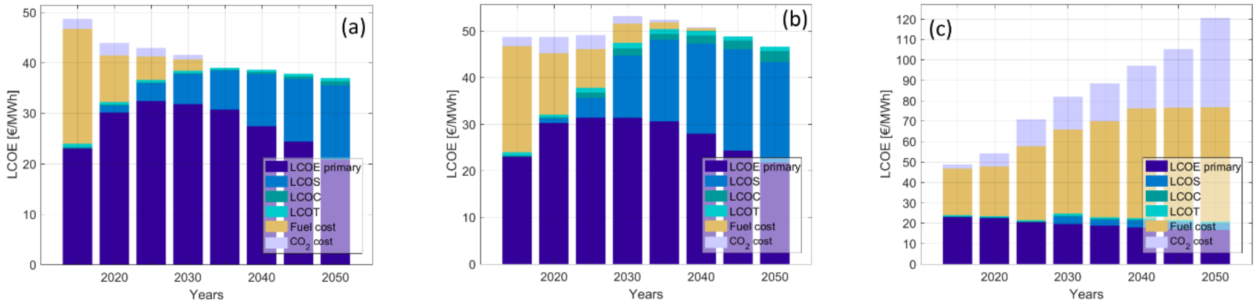

Figure 17. Levelised cost of electricity in the BPS-1 (a), BPS-2 (b) and CPS (c) for the year 2050.

3.8 Greenhouse Gas Emissions

The GHG emissions course in the transition period for all scenarios is depicted in Figure 18. The thick blue bar shows the CO_2 emissions whiles the thin red line indicates the ratio of CO_2 to generated electricity. 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 Figure 18 (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 Figure 18c.

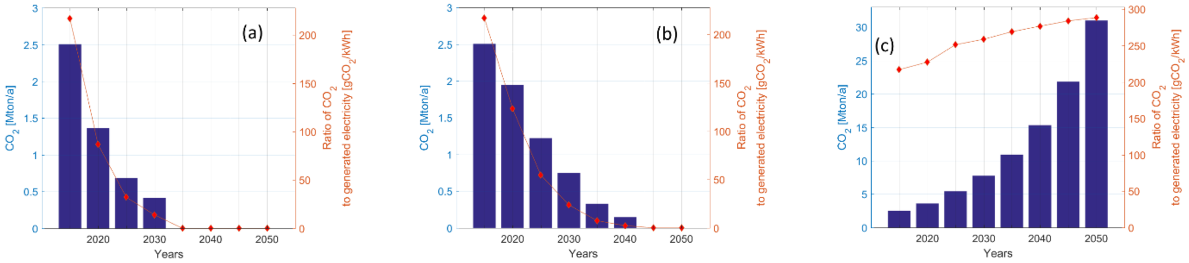

Figure 18. The GHG emissions trajectory in the BPS-1 (a), BPS-2 (b) and CPS (c) during the transition period.

3.9 Energy flow overview

Figure 19 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, Figure 19 (top), the primary energy consists of about 67% fossil fuel which diminish completely in the BPS-1 by 2050 as depicted in the Figure 19 (bottom). In the BPS-1, Figure 19 (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 provided in the Supplementary Material in Appendix (Figure A17-A18).

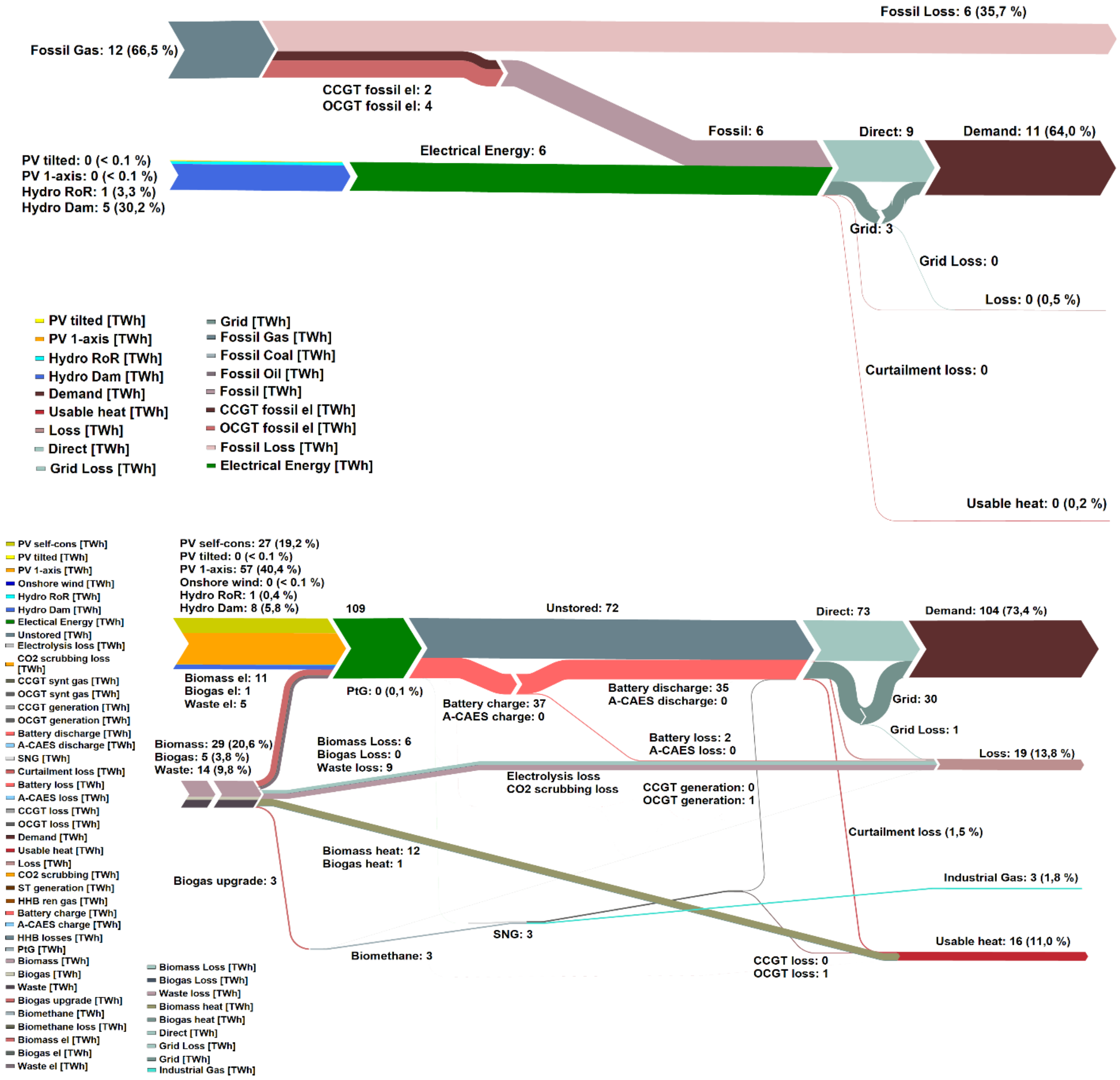

Figure 19. Energy flow of the power sector for 2015 (top) and BPS-1 in 2050 (bottom)

4. DISCUSSION

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

4.1 Outstanding 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 and is expected to host more PV capacity in the future (Quansah et al. 2018). The plausible reason for the high solar PV installed capacity in the upper north in the BPS is due to high solar potential in this region (Quansah et al. 2018) and the subsequent low cost. The study outcome indicates that solar PV emerges as the prime source of electricity supply for Ghana, which is comparable to the finding of (Oyewo et al. 2018) for Nigeria, who conclude that solar PV technology has a pivotal role to play in the Nigerian defossilised power system. Barasa et al. (2018) also conclude that most Sub-Saharan African (SSA) countries can be powered majorly by wind energy and solar PV. In the CPS, most of the electricity is supplied by gas turbines by 2050. The total power generation is dominated by gas turbines 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. 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.

4.2 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 Figure 20. Power systems dominated by solar PV are often characterised by high storage requirement (Solomon et al. 2018; Cebulla et al. 2018; Keiner et al. 2019). Storage technologies improve the system flexibility, particularly battery storage owing to daily discharge and charge. 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 is 5 TWh (97 % and 4.4% respectively) in the CPS. For weekly, seasonal and long-term storages, TES, A-CAES and PtG are employed. Studies have shown that energy storage is needed in power generation with about 50% RE share (Keiner et al. 2019) and the need for seasonal storage becomes apparent when RE share reaches 80% (Keiner et al. 2019; Solomon et al. 2018). Instead, dispatchable RE generation, in particular bioenergy resource and hydropower appears to be sufficient in providing the seasonal balancing as shown in Figure 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 (Barbosa et al. 2016) and West Africa (Oyewo et al. 2019). According to (Barbosa et al. 2016; Oyewo et al. 2019), a 100% RE-based power system can run with very low seasonal storage.

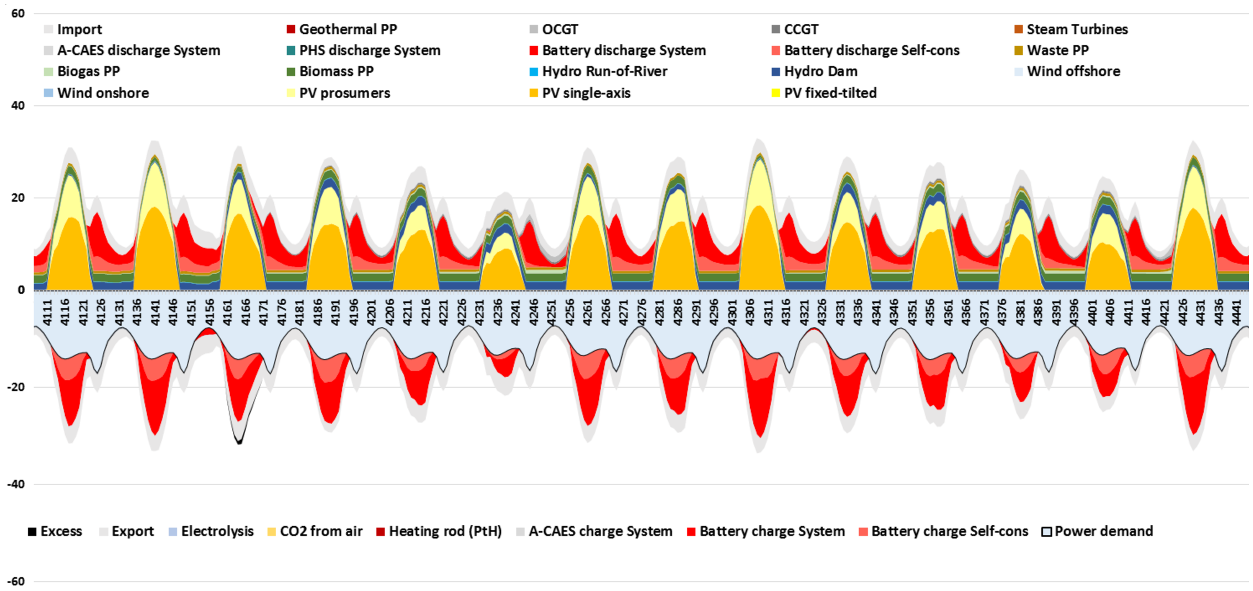

Figure 20. Generation and demand profiles during the monsoon period in the BPS-1 for the year 2050.

The power transmission network furnish the power system, with additional flexibility 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 (Kies et al. 2017), which includes the potential to reduce LCOE and to facilitate high RE penetration (Kies et al. 2017). 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 (Haas et al. 2017).

4.3 The role of bioenergy in RE-dominated systems

Currently, bioenergy contributes the major share of the renewable energy in the world (IEA, 2017). About 47.7% (IEA, 2016b) and 38.5% (IEA 2016a) of the total primary energy demand in Africa and Ghana respectively, is contributed by solid biofuels and waste, which will continue to be an essential energy resource for Africa in the future (IRENA and DBFZ, 2013). The results of this study show that, the bioenergy potential of Ghana as of 2015 was 48.3 TWh. This includes residues which are crop residue, forest residue, animal manure, sewage sludge, and municipal solid waste.

According to (WB, 2015), Ghana has huge untapped arable land of about 20.7% the total land area of Ghana, which could provide more bioenergy potential, especially crop residue, if the efficiency of crop farming practices in Ghana is increased.

In Ghana, biomass is mainly in the traditional form (IRENA and DBFZ, 2013), except for few distribution level biomass power plants of about 100 kW installed capacity (Energy Commission 2018b). Traditional biomass is the unsuitable and unsustainable use of fuel wood, charcoal, tree leaves, animal dung and agricultural residue for cooking, lighting and space heating (IRENA and DBFZ, 2013). Studies have shown that the use of traditional biomass culminates in catastrophic health problems, such as pneumonia, chronic obstructive pulmonary diseases or lung cancer (IRENA and DBFZ, 2013). However, appropriate investments in bioenergy technologies might provide a paradigm shift from traditional to modern biomass use. Wherein solid biofuels are combusted in CHP plants, biogas in gas turbines and liquid biofuels in gas engines (ICE) into heat and power, thereby providing short-term to mid-term and also seasonal balancing of the RE resource dominated energy system. Thereby, ensuring a synergy in seasonal balancing between variable RE sources and biomass utilisation.

Bioenergy is a dispatchable form of RE generation and has the potential of stabilising a power grid dominated by RE resources (IEA, 2019). 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. Whereas, in the BPS-1 it is provided mainly by bioenergy plants, followed by hydropower and gas turbines. The missing bioenergy availability in the BPS-2 is largely compensated by additional capacity as shown in Figure 10. 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. Bioenergy, which is applied extensively to the BPS-1 can be considered as an indirect solar storage (IEA, 2017), in its natural form, thereby compensating for additional batteries, which otherwise might be needed. 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 also 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 Figure 21. Additional information on the curtailment and generation for all scenarios are provided in the Supplementary Material in Appendix (Figure A4).

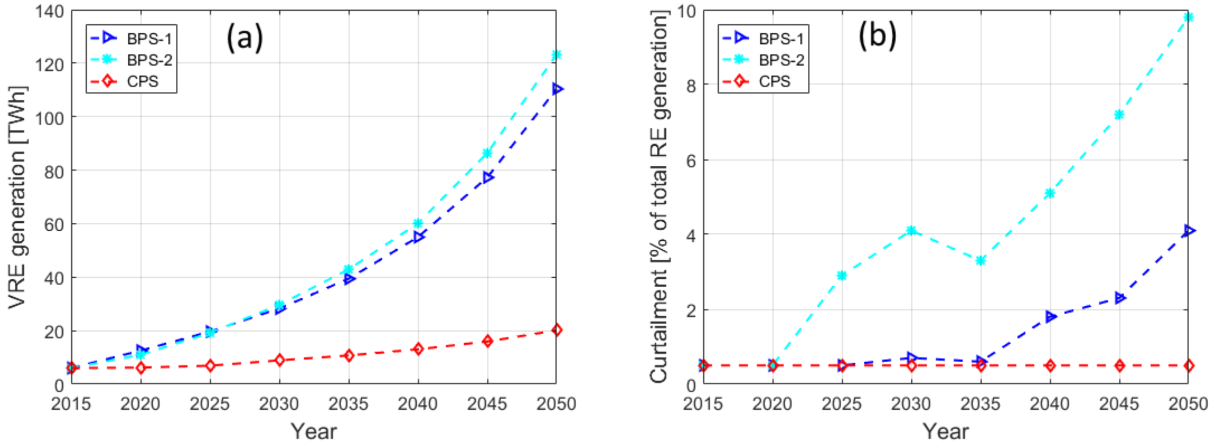

Figure 21. Variable RE generation (a) and curtailment of generation potential (b) in TWh under various scenarios during the transition.

LCOE primary costs are equally higher in the BPS-2 than the BPS-1, because additional installed solar PV capacity is needed to compensate for the missing bioenergy capacity. Although the average LCOE of bioenergy plants of 46 €/MWh is comparatively higher than 23 €/MWh of solar PV plants, about 15 GW of solar PV installed capacity is needed in the BPS-2 to compensate for the 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 5 shows the LCOE difference between BPS-1 and BPS-2.

Table 5. LCOE difference between BPS-1 and BPS-2 for 2050.

	Unit	BPS-1	BPS-2	Difference
LCOE primary total	[€/MWh]	20.7	21.7	1.0
LCOC total	[€/MWh]	0.7	2.4	1.6
LCOS total	[€/MWh]	14.8	21.6	6.8
LCOT total	[€/MWh]	0.7	0.9	0.3
LCOE total	[€/MWh]	37.0	46.6	9.6

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. A fact, which has received less attention than the valuable contribution is provided. The application of sustainable biomass in bioenergy power plants to replace polluting fossil fuels (natural gas and oil) 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 and most importantly, it will provide energy self-sufficiency (security of supply) and additional environmental benefits.

4.4 Benefits of the energy transition

The results, as shown in Table 5 depicts 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 (Oyewo et al. 2019). According to Oyewo et al., (2019), Ghanaian LCOE by 2050 will be in the range of 37.1 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. Figure 22 shows the total annualised cost of all six scenarios during the transition period.

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.

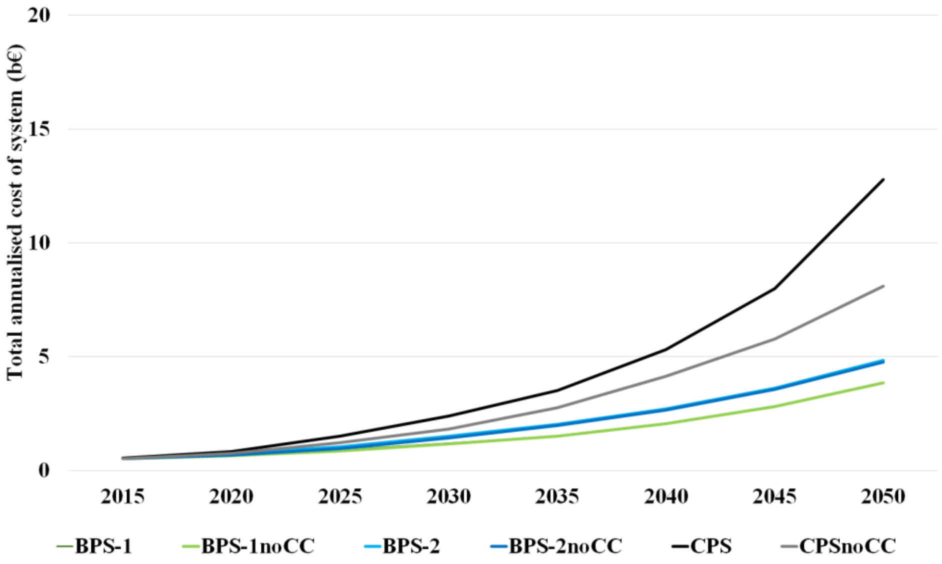

Figure 22. Total system cost per annum comparison for various scenarios during the transition period.

Table 6. Key financial and technical parameters by year 2050 for various 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

Hybrid PV-battery systems appear to be the central and least-cost element for Ghana by 2050, which can be compared to the findings of Oyewo et al. (2018) for the Nigerian and West African power system (Oyewo et al. 2019). In addition, PV (ITRPV, 2019) and battery (Kittner et al. 2017; Schmidt et al. 2017) costs have declined substantially 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. 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 with high fuel cost, 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 as can be seen in Figure 21, 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, since the current power generation portfolio of Ghana has a high share of fossil-based technologies. In short, GHG emissions cost does not significantly affect the power system with high RE resources due to zero GHG emissions.

Currently, natural gas and oil-fired gas turbines account for 65.8% of the country's installed capacity. Natural gas is mainly supplied to Ghana from Nigeria through the West African Gas Pipeline (WAGP) and additional supply from Ghana Natural Gas Company (GNGC) (Atuabo Gas) (Energy Commission, 2018a). Supply from Nigeria has been unreliable due to financial settlements and technical matters, which negatively influenced electricity generation, resulting in frequent load shedding and power outages. In a nutshell, the availability and price of natural gas is a key determinant factor for Ghana's power generation cost and availability. This study illustrates and provides the strategic pathways for a possible transition to a GHG emissions free, secured energy and sustainable power sector for Ghana.

The Government of Ghana plans to invest in coal and nuclear by 2045. These technologies violate the sustainable criteria discussed in (Child et al. 2018) and could become stranded assets (Farfan and Breyer, 2017), given the clear findings of the BPS and the CPS analyses. Investing in new coal and nuclear power plants will contradict Ghana's commitment to cut GHG emissions to zero by 2050, as reported by (Climate Action, 2018). 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 (REN21, 2018) 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 solve the climate change crisis.

5. CONCLUSIONS AND POLICY IMPLICATIONS

The results of this study clearly indicate that Ghana can harness affordable and reliable electricity from 100% RE generation capacity, which would help address the country's long-standing energy poverty and energy security challenges. It is the least-cost to supply 76-92% of Ghana's electricity with solar PV 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. 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 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 solar PV and battery integration in the Ghanaian 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. Commercialisation of sustainable biomass in electricity production will generate a second source of income for both crop and livestock farmers, the Ghanaian forest industry and possibly waste management companies. 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 form a long-term perspective are required. The results of this research have shown that: 1) A fully renewable power system is both technically feasible and economically viable for Ghana and also represents the least cost option in the long-term, when compared to a conventional power system. 2) The variable nature of solar energy can be balanced effectively by bioenergy. 3) Ghana has enough bioenergy potential of 48.3 TWh to create a good synergy between PV-battery driven and bioenergy balanced RE power system and hydropower complementing the balancing effect. Further research for Ghana will be initiated in future to incorporate all energy sectors.

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1. A fully renewable power system is both technically feasible and economically viable for Ghana and also represents the least cost option in the long-term when compared to a conventional power system.
2. The variable nature of solar energy can be balance effectively by bioenergy.
3. Ghana has enough bioenergy potential of 48.3 TWh to create a good synergy between a PV-battery driven and bioenergy balanced RE power system and of course hydropower complementing the balancing effect.

Further research for Ghana will be initiated in future to incorporate all energy sectors.

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APPENDIX

Table A1: Full Load Hours BPS-1

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	[h]	1589	1589	1589	1588	1588	1588	1588	1385
PV single-axis tracking	[h]	1900	2064	2015	2015	1924	1945	1962	1980
Wind energy	[h]	0	618	689	711	756	742	730	685
Geothermal power	[h]	0	0	0	0	0	0	0	0
CSP	[h]	0	1366	1562	1501	1523	1523	1523	1523
Hydropower	[h]	4231	4231	4231	4231	4231	4231	4231	4231
Biomass PP	[h]	0	8322	8322	8322	8322	8062	7076	6929
Waste PP	[h]	0	8322	8322	8322	8322	8322	8322	8322
Biogas PP	[h]	0	8322	8322	7043	1924	2142	2068	1160
Biogas Digester	[h]	0	8322	8322	8319	8321	5494	8101	7126
Biogas Upgrade	[h]	0	8322	8322	8322	8322	8322	8322	8322
Battery	[h]	0	1811	1821	1831	1744	1833	1862	1847
PHES	[h]	0	0	0	0	0	0	0	0
TES	[h]	0	5420	5420	5420	2695	6761	8102	8500
CAES	[h]	0	1918	4121	3023	738	1496	2015	2252
PtSNG	[h]	0	729	869	8310	0	0	2189	2254
CCGT PP	[h]	6451	6132	3504	1753	415	479	559	556
OCGT PP	[h]	4327	1752	876	876	115	36	136	510
Coal PP	[h]	0	0	0	0	0	0	0	0
Oil PP	[h]	0	0	0	0	0	0	0	0
Nuclear PP	[h]	0	0	0	0	0	0	0	0

Table A2: Full Load Hours BPS-1noCC

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	[h]	1589	1589	1589	1588	1588	1588	1588	1480
PV single-axis tracking	[h]	1900	2064	2015	2015	1920	1945	1962	1980
Wind energy	[h]	0	732	721	720	748	732	743	718
Geothermal power	[h]	0	0	0	0	0	0	0	0
CSP	[h]	0	1479	1615	1431	1447	1447	1447	1447
Hydropower	[h]	4231	4231	4231	4231	4231	4231	4231	4231
Biomass PP	[h]	0	8322	8322	8322	8322	8063	7065	6862
Waste PP	[h]	0	8322	8322	8322	8322	8322	8322	8322
Biogas PP	[h]	0	8322	8322	7070	2134	2370	2264	1270
Biogas Digester	[h]	0	8322	8322	8309	8322	5769	8009	7198
Biogas Upgrade	[h]	0	8322	8322	8322	8322	8322	8322	8322
Battery	[h]	0	1811	1821	1832	1752	1833	1860	1849
PHES	[h]	0	0	0	0	0	0	0	0
TES	[h]	0	5420	5420	5420	2744	6775	8175	8643
CAES	[h]	0	371	604	2315	761	1469	1973	2311
PtSNG	[h]	0	704	740	8121	0	0	1478	1579
CCGT PP	[h]	6451	6132	3504	1753	820	487	466	457
OCGT PP	[h]	4327	1752	876	876	122	47	172	520
Coal PP	[h]	0	0	0	0	0	0	0	0
Oil PP	[h]	0	0	0	0	0	0	0	0
Nuclear PP	[h]	0	0	0	0	0	0	0	0

Table A3: Full Load Hours BPS-2

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	[h]	1589	1589	1589	1589	1589	1589	1589	1500
PV single-axis tracking	[h]	1900	2046	1981	1996	1980	1980	1977	1977
Wind energy	[h]	0	744	802	687	681	662	667	669
Geothermal power	[h]	0	0	0	0	0	0	0	0
CSP	[h]	0	1574	1429	1419	1416	1424	1419	1419
Hydropower	[h]	4231	4231	4231	4231	4231	4231	4231	4231
Biomass PP	[h]	0	0	0	0	0	0	0	0
Waste PP	[h]	0	0	0	0	0	0	0	0
Biogas PP	[h]	0	0	0	0	0	0	0	0
Biogas Digester	[h]	0	0	0	0	0	0	0	0
Biogas Upgrade	[h]	0	0	0	0	0	0	0	0
Battery	[h]	0	1811	1816	1859	1848	1960	1889	1873
PHES	[h]	0	0	0	0	0	0	0	0
TES	[h]	0	5420	5420	5420	7928	8625	8491	8547
CAES	[h]	0	1553	1983	1517	1633	2091	2062	2116
PtSNG	[h]	0	1893	1807	323	1924	2641	2901	5150
CCGT PP	[h]	6451	8322	5875	2628	1752	660	958	1197
OCGT PP	[h]	4327	1752	876	876	175	136	274	321
Coal PP	[h]	0	0	0	0	0	0	0	0
Oil PP	[h]	0	0	0	0	0	0	0	0
Nuclear PP	[h]	0	0	0	0	0	0	0	0

Table A4: Full Load Hours BPS-2noCC

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	[h]	1589	1589	1589	1589	1589	1589	1589	1492
PV single-axis tracking	[h]	1900	2016	1951	1989	1979	1980	1981	1979
Wind energy	[h]	0	712	707	761	723	672	712	656
Geothermal power	[h]	0	0	0	0	0	0	0	0
CSP	[h]	0	1487	1527	1461	1554	1405	1493	1587
Hydropower	[h]	4231	4231	4231	4231	4231	4231	4231	4231
Biomass PP	[h]	0	0	0	0	0	0	0	0
Waste PP	[h]	0	0	0	0	0	0	0	0
Biogas PP	[h]	0	0	0	0	0	0	0	0
Biogas Digester	[h]	0	0	0	0	0	0	0	0
Biogas Upgrade	[h]	0	0	0	0	0	0	0	0
Battery	[h]	0	1811	1795	1862	1868	1926	1869	1868
PHES	[h]	0	0	0	0	0	0	0	0
TES	[h]	0	5420	5420	5420	7791	8302	8571	8576
CAES	[h]	0	1705	1040	1304	1585	1781	2196	2235
PtSNG	[h]	0	1781	3705	484	2436	1251	2776	3252
CCGT PP	[h]	6451	8322	6207	6218	3425	648	1250	1502
OCGT PP	[h]	4327	23	858	30	23	123	300	373
Coal PP	[h]	0	0	0	0	0	0	0	0
Oil PP	[h]	0	0	0	0	0	0	0	0
Nuclear PP	[h]	0	0	0	0	0	0	0	0

Table A5: Full Load Hours CPS

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	[h]	1589	1503	1494	1491	1491	1490	1490	1490
PV single-axis tracking	[h]	1900	1881	1881	1881	1881	1881	1881	1881
Wind energy	[h]	0	679	679	679	679	679	679	679
Geothermal power	[h]	0	0	0	0	0	0	0	0
CSP	[h]	0	0	0	0	0	0	0	0
Hydropower	[h]	4231	4231	4231	4231	4231	4231	4231	4231
Biomass PP	[h]	0	0	0	8322	8322	8322	8322	8322
Waste PP	[h]	0	0	0	0	0	0	0	0
Biogas PP	[h]	0	0	0	0	0	0	0	0
Biogas Digester	[h]	0	0	0	0	0	0	0	0
Biogas Upgrade	[h]	0	0	0	0	0	0	0	0
Battery	[h]	0	3235	2654	2978	2646	1456	1474	1461
PHES	[h]	0	0	0	0	0	0	0	0
TES	[h]	0	5420	5420	5420	1	3	6	10
CAES	[h]	0	1461	1206	1558	1371	813	899	1201
PtSNG	[h]	0	946	864	0	1	1	1	1
CCGT PP	[h]	6451	7008	7008	7008	7446	7446	7446	6833
OCGT PP	[h]	4327	876	876	1008	954	876	876	876
Coal PP	[h]	0	0	0	0	0	0	0	0
Oil PP	[h]	0	0	0	0	0	0	0	0
Nuclear PP	[h]	0	0	0	0	0	0	0	0

Table A6: Full Load Hours CPSnoCC

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	[h]	1589	1503	1494	1491	1491	1490	1490	1490
PV single-axis tracking	[h]	1900	1881	1881	1881	1881	1881	1881	1881
Wind energy	[h]	0	679	679	679	679	679	679	679
Geothermal power	[h]	0	0	0	0	0	0	0	0
CSP	[h]	0	0	0	0	0	0	0	0
Hydropower	[h]	4231	4231	4231	4231	4231	4231	4231	4231
Biomass PP	[h]	0	0	0	8322	8322	8322	8322	8322
Waste PP	[h]	0	0	0	0	0	0	0	0
Biogas PP	[h]	0	0	0	0	0	0	0	0
Biogas Digester	[h]	0	0	0	0	0	0	0	0
Biogas Upgrade	[h]	0	0	0	0	0	0	0	0
Battery	[h]	0	3327	975	2922	1937	2065	1553	1537
PHES	[h]	0	0	0	0	0	0	0	0
TES	[h]	0	5420	5420	5420	0	2	1	9
CAES	[h]	0	1650	365	1545	1004	1317	587	888
PtSNG	[h]	0	1393	0	611	2	2	210	2
CCGT PP	[h]	6451	7008	7008	7008	7008	7008	7008	7008
OCGT PP	[h]	4327	876	876	876	876	879	876	876
Coal PP	[h]	0	0	0	0	0	0	0	0
Oil PP	[h]	0	0	0	0	0	0	0	0
Nuclear PP	[h]	0	0	0	0	0	0	0	0

Table A7. Crop residue energy potential of Ghana (FAOSTAT 2015a) .

Index	**Crop types**	**Productions**	**Residue type**	**Residue to product ratio**	**Residue (Wet)**	**Lower heating value**	**Residues energy potentials**	**Potentials**
		[tonnes]		**(RPR)**	**[tonnes]**	**[MJ/kg]**	**[PJ]**	**[TWh$_{th}$]**
1	Sorghum	262,652	Stalk	2.6	240,851	12.38	2.98	0.83
2	Millet	157,369	Stalk/straw	3.0	165,237	12.39	2.05	0.57
3	Rice	641,492	Straw/husk	1.5	336,783	19.33	6.51	1.81
4	Sugarcane	149,589	Bagasse	0.3	15,707	18.10	0.28	0.08
5	Beans	201,150	Straw	2.5	176,006	17.00	2.99	0.83
6	Cashew nuts, with shell	50,000	Nut shells	2.0	35,000	17.00	0.60	0.17
7	Sweet potatoes	140,732	Stalk	0.6	29,554	17.00	0.50	0.14
8	Groundnuts	417,199	Shells	2.5	365,049	17.58	6.42	1.78
9	Yam	7,296,150	Stalk	0.2	510,731	17.58	8.98	2.49
10	Banana	87,505	Pseudo stem	1.0	30,627	17.40	0.53	0.15
11	Plantain	3,952,421	Pseudo stem	1.0	1,383,347	17.40	2.07	6.69
12	Coconut	380,380	Shell/fronds/ Husk	0.6	79,880	18.62	1.49	0.41

13	Oil palm fruit	2,443,000	Empty fruit bunch	0.25	213,763	18.83	4.03	1.12
14	Coffee	736	Husk	2.1	541	12.38	0.01	0.00
15	Cocoa	858,720	Pods, husk	1.0	300,552	15.48	4.65	1.29
16	Cassava	17,212,756	Stalk	0.2	1,204,893	17.50	21.09	5.86
17	Maize	1,691,644	Stalk/Stover/cob	1.5	888,113	19.66	17.46	4.85
Total		**35,943,495**			**5,976,634**		**104.63**	**29.06**

Table A8. Wood residue energy potential of Ghana (FAOSTAT 2015b).

Index	**wood types**	**Production(m^3)**	**Average density (kg/m^3)**	**Production (tonnes)**	**Residue to product ratio (RPR)**	**Residue (Wet tonnes)**	**Moisture content (%)**	**Lower heating value dry (MJ/kg)**	**Residues energy potentials(PJ)**	**Potentials (TWh)**
1	Wood fuel, coniferous	0	300	0	0.5	0.00	18	17	0	0.00
2	Wood fuel, non-coniferous	44,018,427	300	13,205,528	0.5	2,310,967	18	17	32.21	8.95
3	Saw logs and veneer logs, non-coniferous	1,860,000	300	558,000	0.5	97,650	18	17	1.36	0.38

4	Other industrial round wood, coniferous	50,000	300	15,000	0.5	2,625	18	17	0.04	0.01
5	Other industrial round wood, non-coniferous	700,000	300	210,000	0.5	36,750	18	17	0.51	0.14
6	Wood charcoal	1,887,538*	300	1,887,538	0.5	330,319	18	17	4.60	1.28
7	Sawn wood, coniferous	10,000	300	3,000	0.5	525	18	17	0.01	0.00
8	Sawn wood, non-coniferous all	524,000	300	157,200	0.5	27,510	18	17	0.38	0.11
9	Veneer sheets	105,000	300	31,500	0.5	5,512	18	17	0.08	0.02
10	Plywood	180,000	300	54,000	0.5	9,450	18	17	0.13	0.04
11	Particle board	8,000	300	2,400	0.5	420	18	17	0.01	0.00
Total		**49,342,965**		**16,124,166**		**2,821,729**			**39.33**	**10.92**

* Value is in tonnes.

Table A9. Manure production from Livestock per annum (FAOSTAT 2015c) .

Animal type	Population	Excreta/animal /annum(tonnes)	Recovery/use factor	Total manure (tonnes, wet)	Moisture content (%)	Total Manure (tonnes dry)
Cattle (Dairy)	1,213,800	22.3	0.8	21,654,192	50	10,827,096
Cattle (beef)	520,200	8.8		3,662,208	50	1,831,104
Goats	6,352,000	1.1		5,589,760	50	2,794,880
Pigs	730,000	1.9		1,109,600	50	554,800
Poultry	71,594,000	0.047		2,691,934	50	1,345,967
sheep	4,522,000	0.4		1,447,040	50	723,520
Total	**84,932,000**			**36154734**		**18,077,367**

Table A10. Bio-waste (kitchen waste) production per annum (Miezah et al. 2015) .

kg/capita/d	Days/a	kg/capita/a	Population	Recovery/use factor	ton/a
0.2863	365	104.49	27,700,000	0.8	2,315,709

Table A11. Sewage sludge per annum (Colón et al. 2015) .

kg/capita/d	days of year	kg/capita/a	Population	kg/a	t/a	Recovery/use factor (80%)
0.35	365	127.75	27,700,000	3,538,675,000	3,538,675	2,830,940

Table A12. Anaerobic digestion process producing biogas (SGTC 2015).

Index	**Feedstock**	**waste (t/a)**	**Total Solid - TS (%)**	**TS (t/a)**	**Volatile solid (VS) from TS (%)**	**VS (t/a)**	**Biogas yield (m^3/tvs)**	**Biogas (m^3/a)**	**Methane share (%)**	**Methane content (m^3/a)**	**Methane Energy content (kWh/m^3)**	**Energy content (TWh)**
1	cattle manure	20,253,120	8.50	1,721,515	80	1,377,212	250	344,303,040	65	223,796,976	9.97	2.23
2	Goats manure	4,471,808	7.00	313,027	77.5	242,596	312.5	75,811,120	70	53,067,784	9.97	0.53
3	Pigs manure	1,109,600	5.50	61,028	75	45,771	375	17,164,125	75	12,873,094	9.97	0.13
4	Poultry manure	2,691,934	20.00	538,387	75	403,790	475	191,800,326	70	134,260,228	9.97	1.34
5	Sewage sludge	2,830,940	5.00	141,547	65	92,006	300	27,601,665	65	17,941,082	9.97	0.18
6	Food waste	2,315,709	10.00	231,571	80	185,257	550	101,891,192	75	76,418,394	9.97	0.76
7	sheep manure	1,447,040	7.00	101,293	77.5	78,502	312.5	24,531,850	70	17,172,295	9.97	0.17
Total		**35,120,151**										**5.34**

Table A13. Municipal solid waste (without bio-waste) (Miezah et al. 2015).

kg/capita/d	Days/a	kg/capita/a	Population	kg/a	(%) counted as biogenic fraction	Lower heating value (MJ/kg)	Energy Potential (TJ)	s/h	TWh
0.1833	365	66.9045	27,700,000	1,853,254,650	0.4615	12.5	10691	3600	**2.97**

Table A25: Levelised cost of electricity primary total (LCOE primary total), Levelised cost of curtailment (LCOC), Levelised cost of storage (LCOS), Levelised cost of transmission (LCOT), Levelised cost of import (LCOI) and Levelised cost of electricity (LCOE) for the years 2015 to 2050 for all scenarios

BPS-1	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE primary total	[€/MWh,el]	47.73	41.84	38.72	34,93	30.69	27.39	24.37	20.74
LCOC total	[€/MWh,el]	0.24	0.23	0.20	0.24	0.17	0.42	0.48	0.74
LCOS total	[€/MWh,el]	0.00	1.32	3.55	5.92	7.74	10.32	12.41	14.81
LCOT total	[€/MWh,el]	0.70	0.50	0.46	0.46	0.37	0.47	0.57	0.67
LCOI total	[€/MWh,el]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LCOE total	[€/MWh,el]	48.68	43.89	42.93	41.55	38.97	38.60	37.83	36.97
BPS-1noCC									
LCOE primary total	[€/MWh,el]	45.78	40.15	37.06	34.49	31.29	27.30	24.32	20.73
LCOC total	[€/MWh,el]	0.23	0.21	0.19	0.53	0.17	0.43	0.48	0.75
LCOS total	[€/MWh,el]	0.00	1.32	3.55	5.28	6.99	1.,26	1.,37	1.73
LCOT total	[€/MWh,el]	0.69	0.48	0.45	0.44	0.36	0.47	0.57	0.68
LCOI total	[€/MWh,el]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LCOE total	[€/MWh,el]	46.70	42.17	41.24	40.73	38.82	38.46	37.74	36.89
BPS-2									
LCOE primary total	[€/MWh,el]	47.73	46.84	42.70	37.04	32.61	28.67	24.33	21.73
LCOC total	[€/MWh,el]	0.24	0.25	1.11	1.50	1.25	1.74	1.88	2.38
LCOS total	[€/MWh,el]	0.00	1.04	4.29	13.36	17.49	19.34	21.70	21.57
LCOT total	[€/MWh,el]	0.70	0.54	1.00	1.25	1.05	0.97	0.88	0.92
LCOI total	[€/MWh,el]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LCOE total	[€/MWh,el]	48.68	48.67	49.09	53.14	52.41	50.73	48.79	46.60

BPS-2noCC									
LCOE primary total	[€/MWh,el]	45.78	42.24	41.20	36.55	33.16	28.46	26.36	24.21
LCOC total	[€/MWh,el]	0.23	0.22	0.74	1.48	1.18	1.54	2.12	2.95
LCOS total	[€/MWh,el]	0.00	1.04	3.49	11.29	16.00	18.96	18.60	17.75
LCOT total	[€/MWh,el]	0.69	0.54	0.64	0.96	0.96	0.94	1.01	1.04
LCOI total	[€/MWh,el]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LCOE total	[€/MWh,el]	46.70	44.04	46.08	50.28	51.30	49.90	48.09	45.96
CPS									
LCOE primary total	[€/MWh,el]	47.73	53.22	69.44	76.72	84.36	92.53	100.69	116.35
LCOC total	[€/MWh,el]	0.24	0.25	0.34	0.36	0.39	0.42	0.45	0.50
LCOS total	[€/MWh,el]	0.00	0.00	0.00	3.67	2.86	3.51	3.49	3.01
LCOT total	[€/MWh,el]	0.70	0.63	0.57	1.05	0.80	0.64	0.59	0.70
LCOI total	[€/MWh,el]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LCOE total	[€/MWh,el]	48.68	54.10	70.34	81.80	88.41	97.10	105.22	120.55
CPSnoCC									
LCOE primary total	[€/MWh,el]	45.78	46.84	56.24	60.44	66.18	72.52	72.75	72.71
LCOC total	[€/MWh,el]	0.23	0.23	0.28	0.29	0.31	0.34	0.33	0.33
LCOS total	[€/MWh,el]	0.00	0.00	0.00	0.84	2.02	2.27	2.71	2.88
LCOT total	[€/MWh,el]	0.69	0.61	0.51	0.54	0.49	0.51	0.41	0.51
LCOI total	[€/MWh,el]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LCOE total	[€/MWh,el]	46.70	47.68	57.03	62.12	69.00	75.64	76.21	76.42

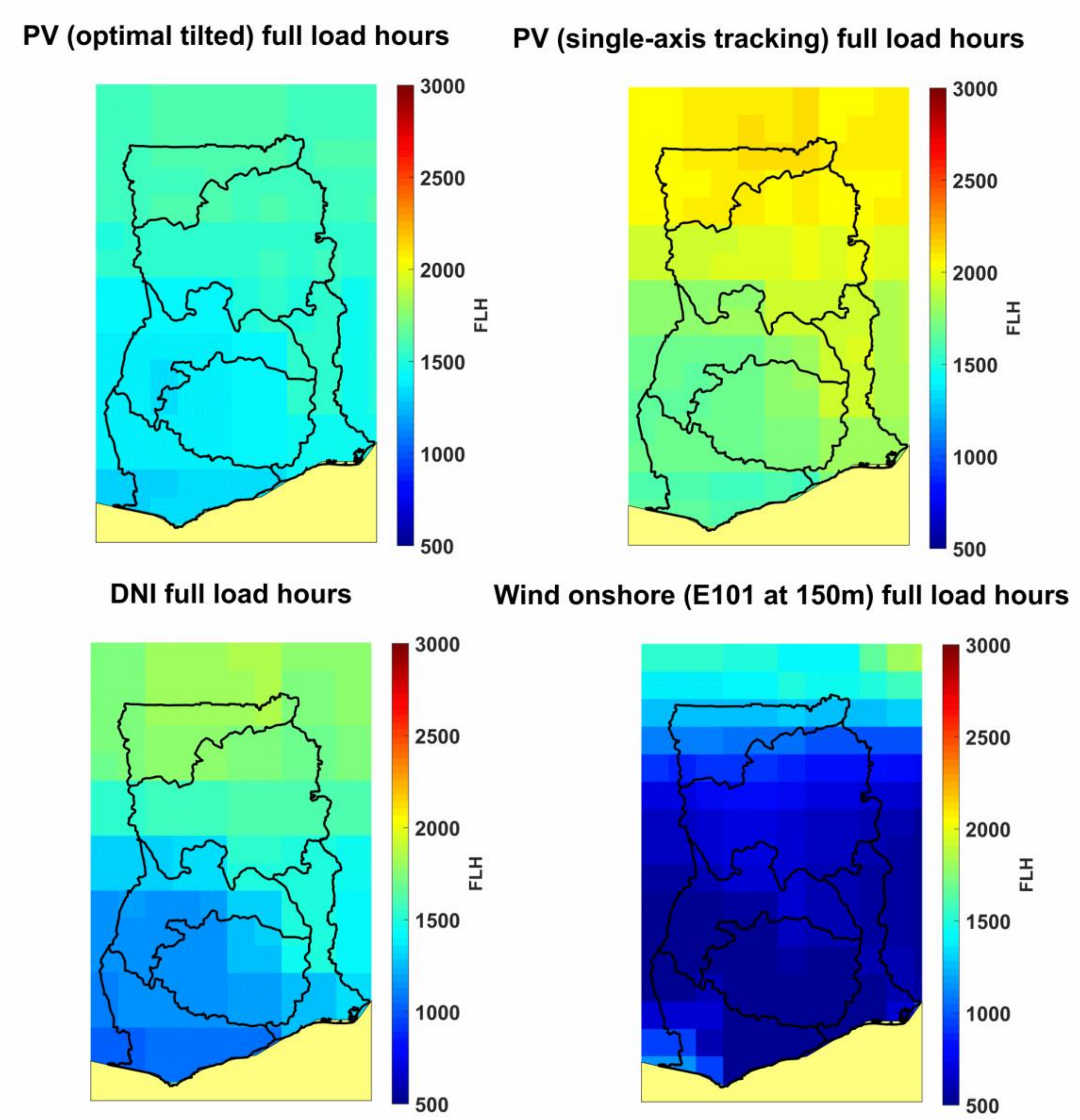


Figure A1: Aggregated feed-in profiles for optimally tilted (top left) and single-axis tracking PV (top right), CSP solar field (bottom left), and wind power plants (bottom right) in Ghana.

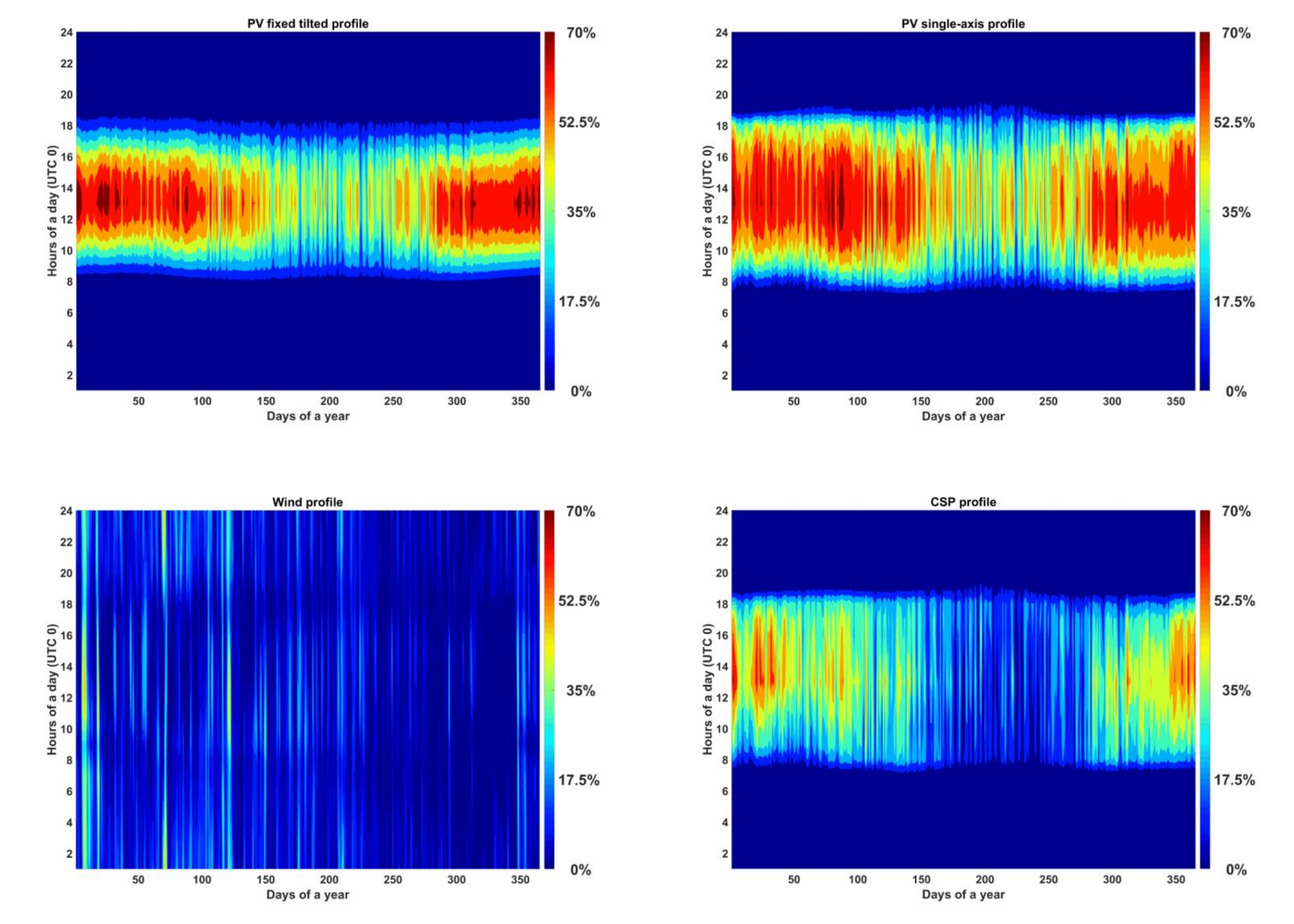


Figure A2: Solar PV fixed tilted (top left), PV single-axis tracking (top right), Wind (bottom left) and CSP (bottom right) generation profiles for Ghana.

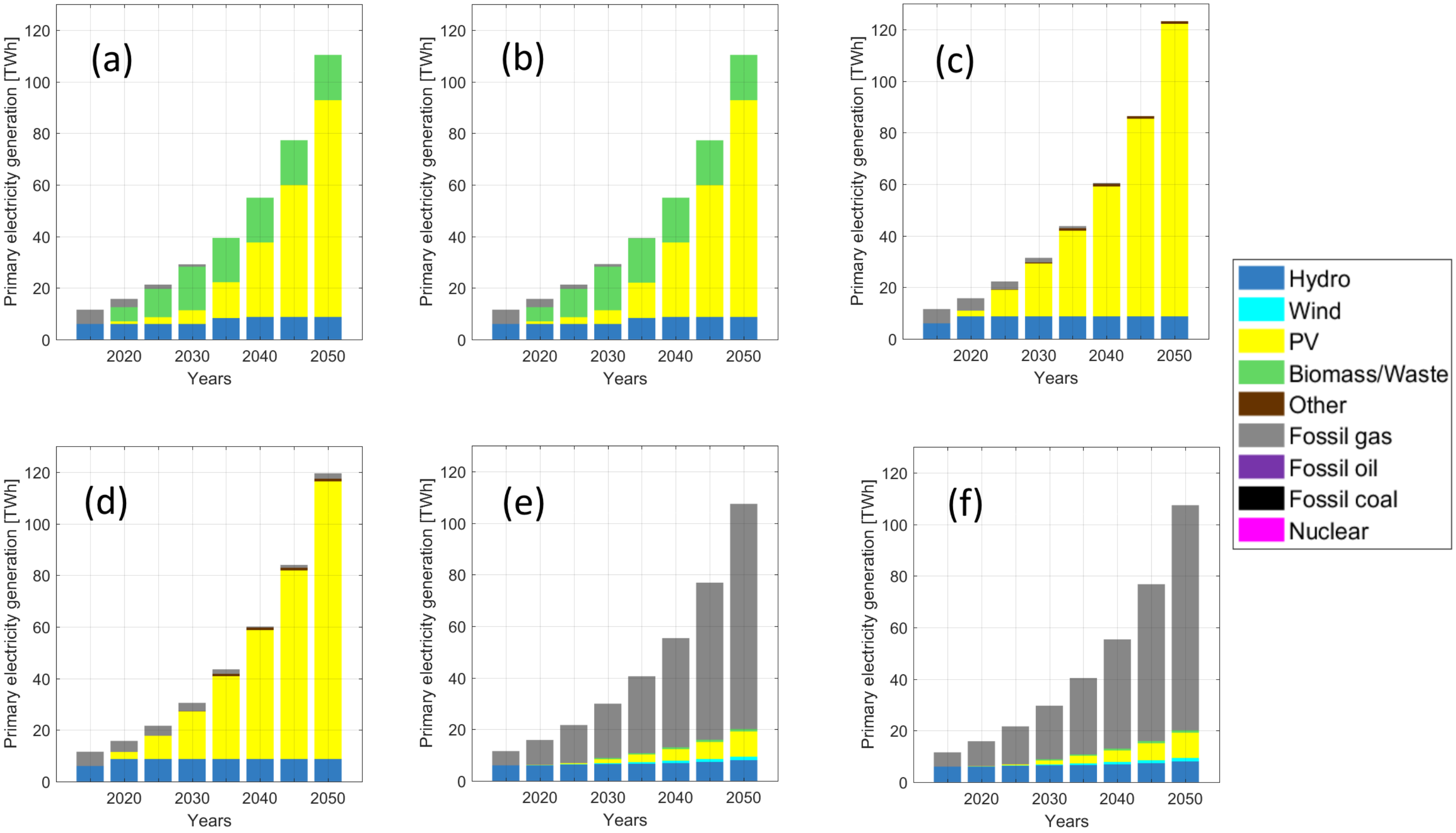


Figure A3: Primary electricity generation for scenarios BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) from 2015 to 2050.

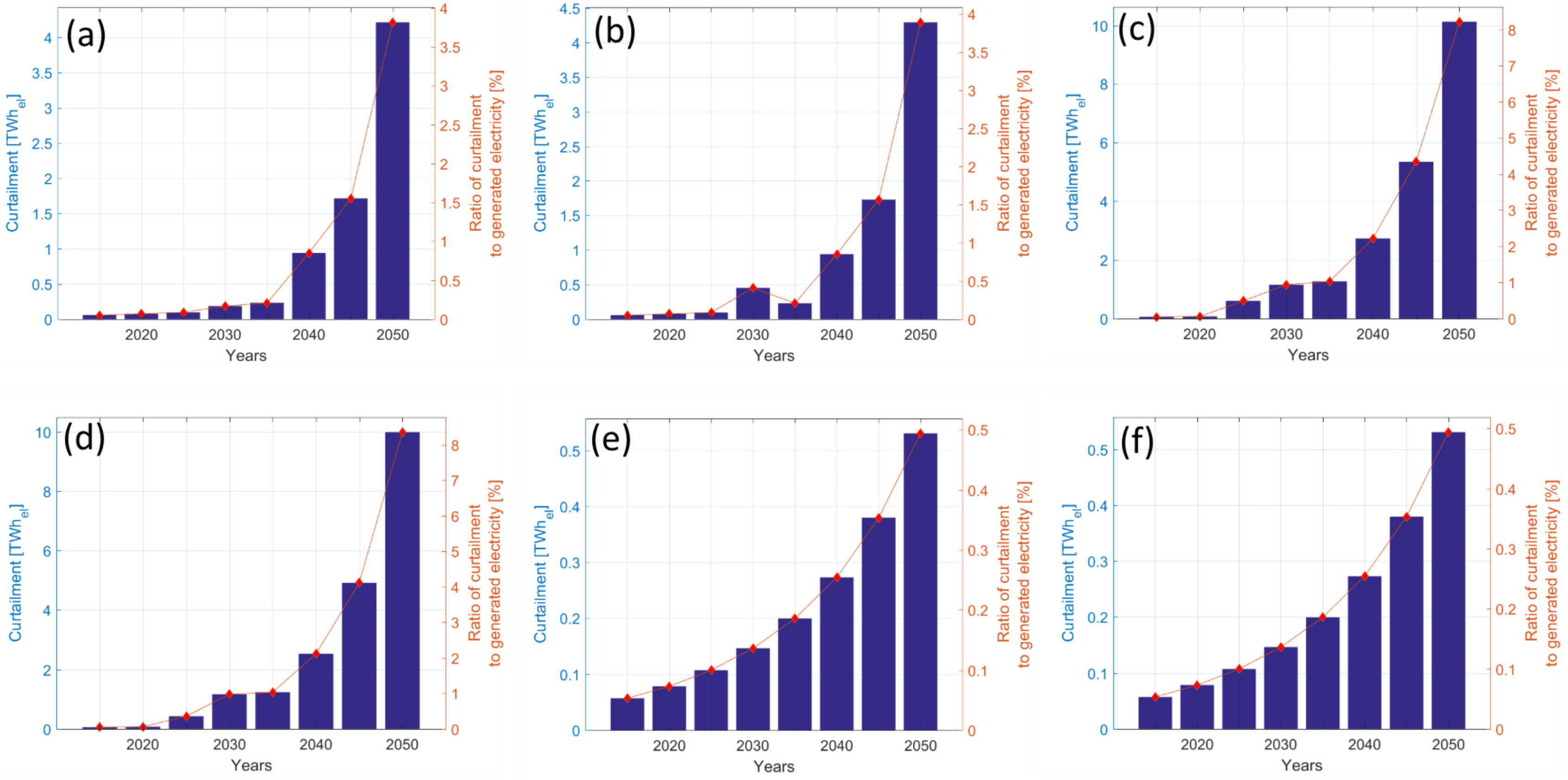


Figure A4: Curtailment generation in TWh$_{el}$ for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the years 2015 to

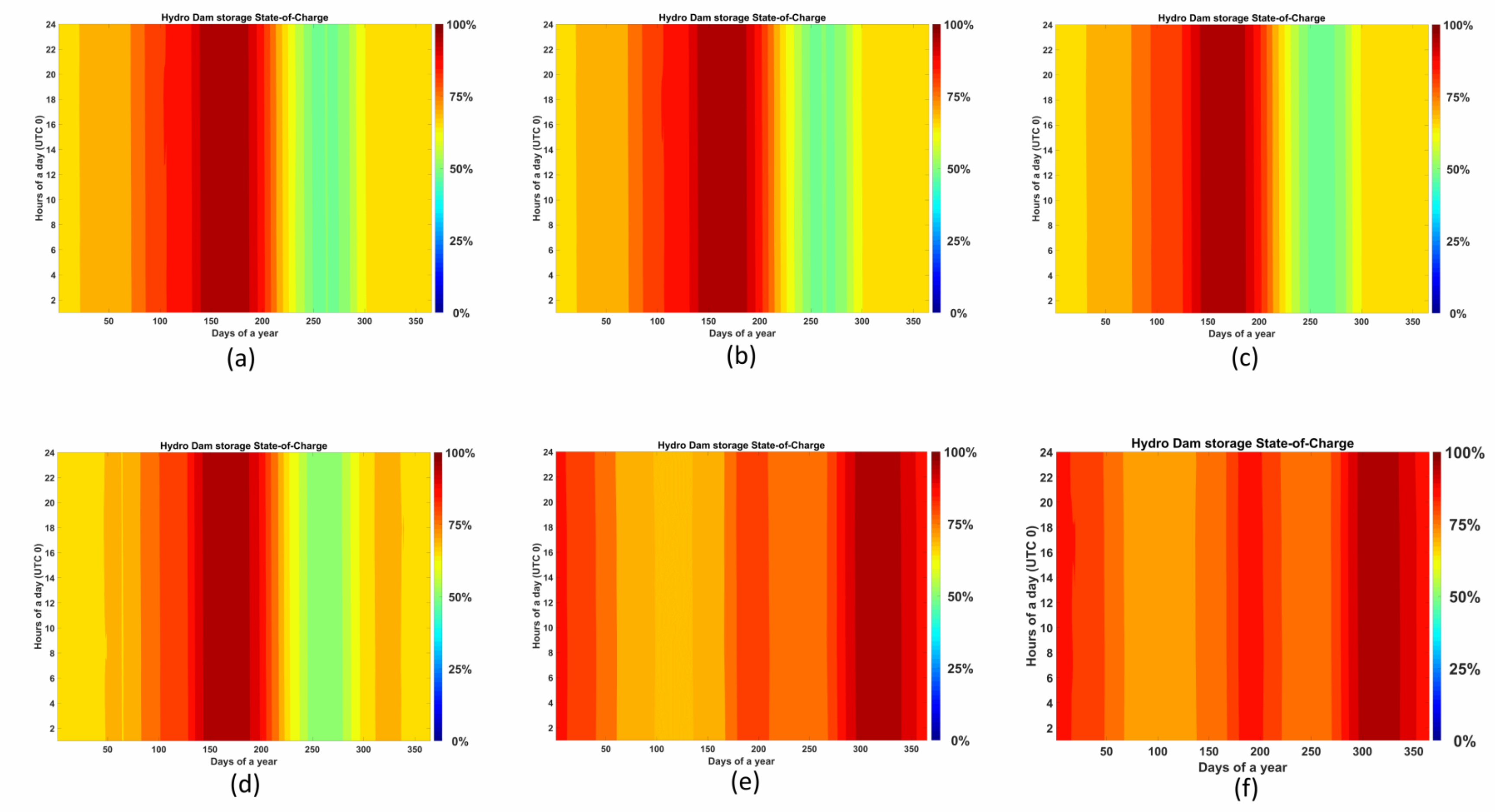


Figure A5: Hydro reservoir (dam) storage State-of-Charge for scenarios BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

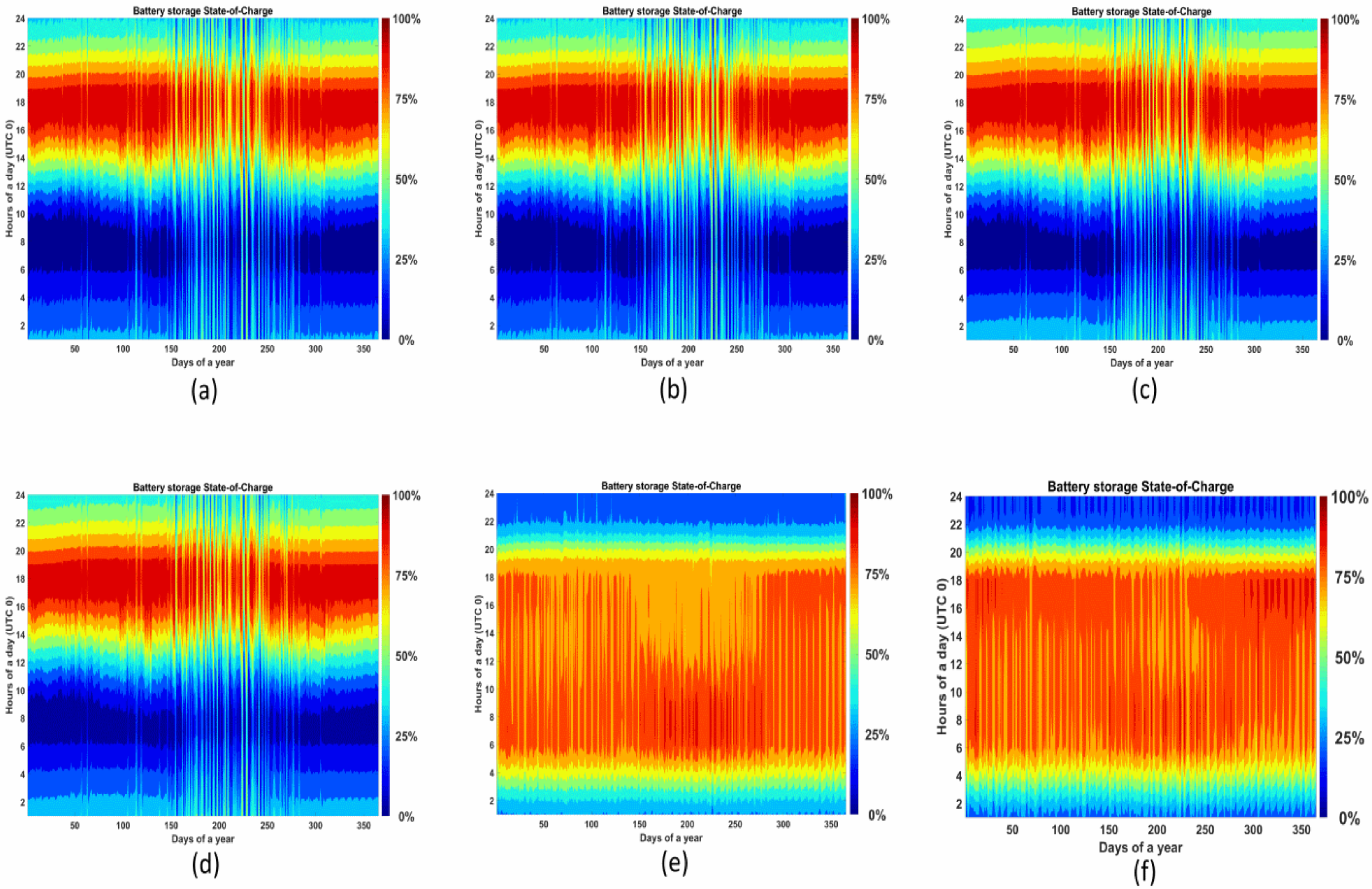


Figure A6: Battery storage State-of-Charge for scenarios BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

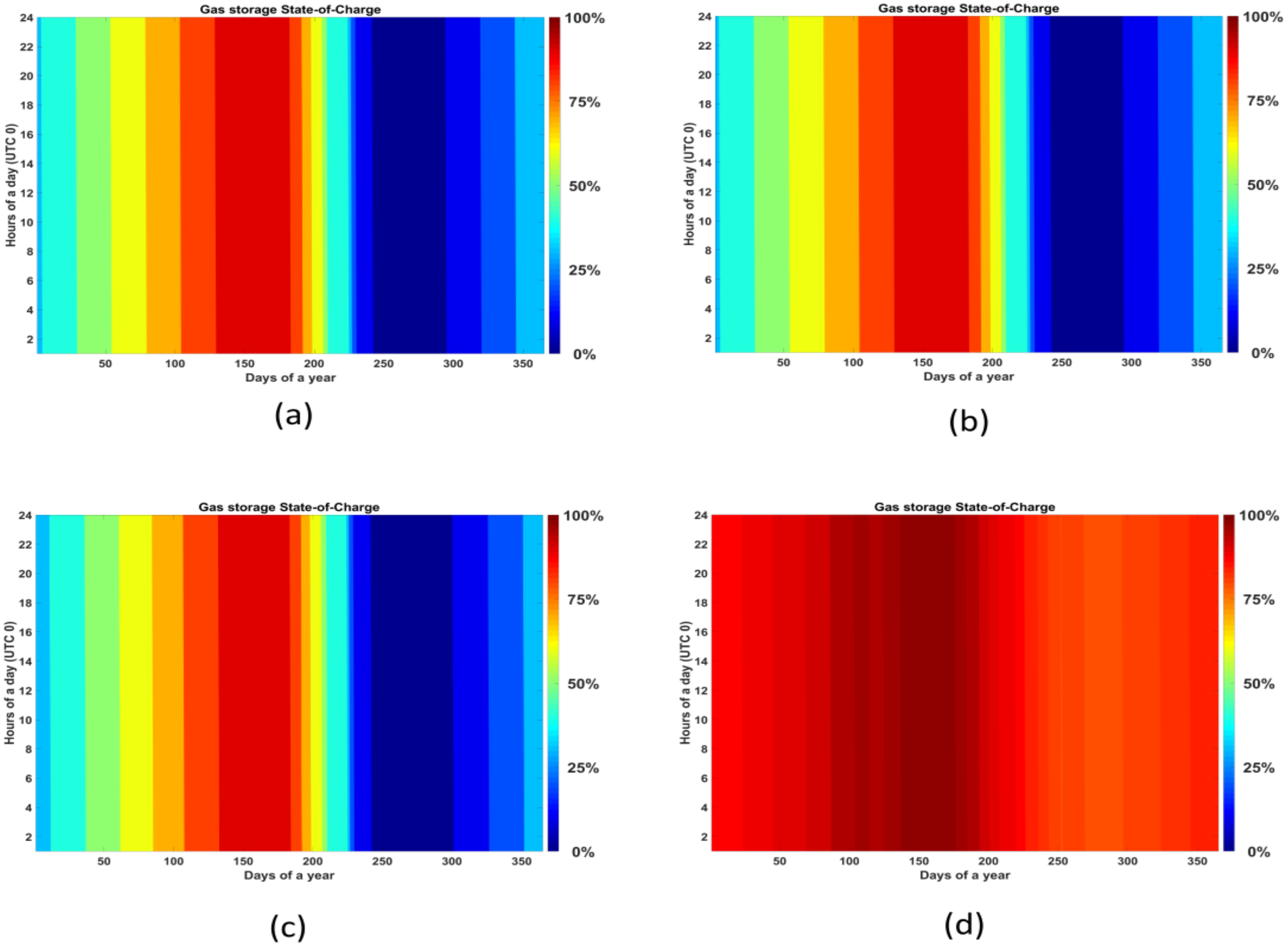
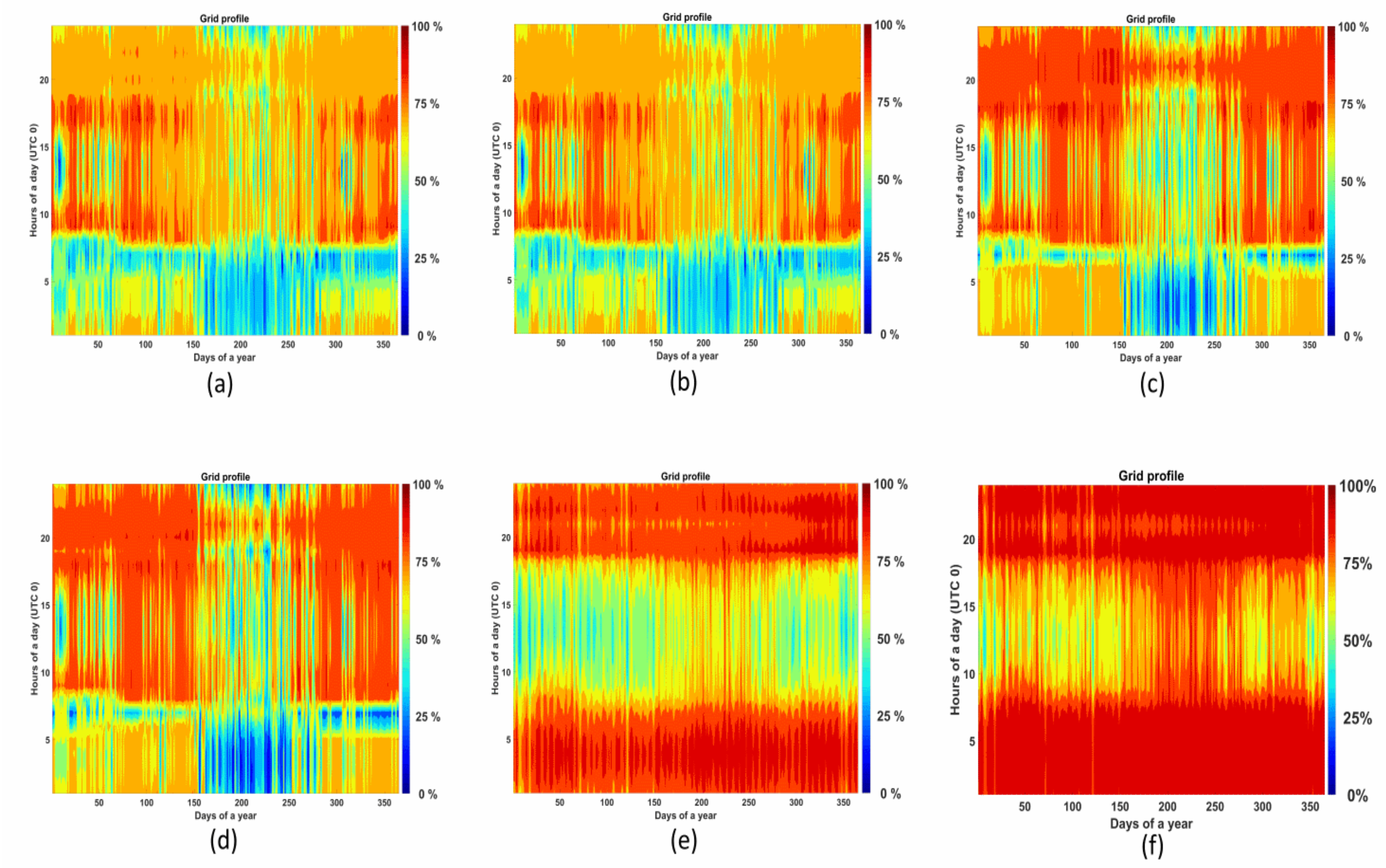


Figure A7: Gas storage State-of-Charge for scenarios BPS-1 (a), BPS-1noCC (b), BPS-2 (c) and BPS-2noCC (d) for the year 2050.



(a) (b) (c) (d) (e) (f)

Figure A8: Grid profiles for scenarios BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

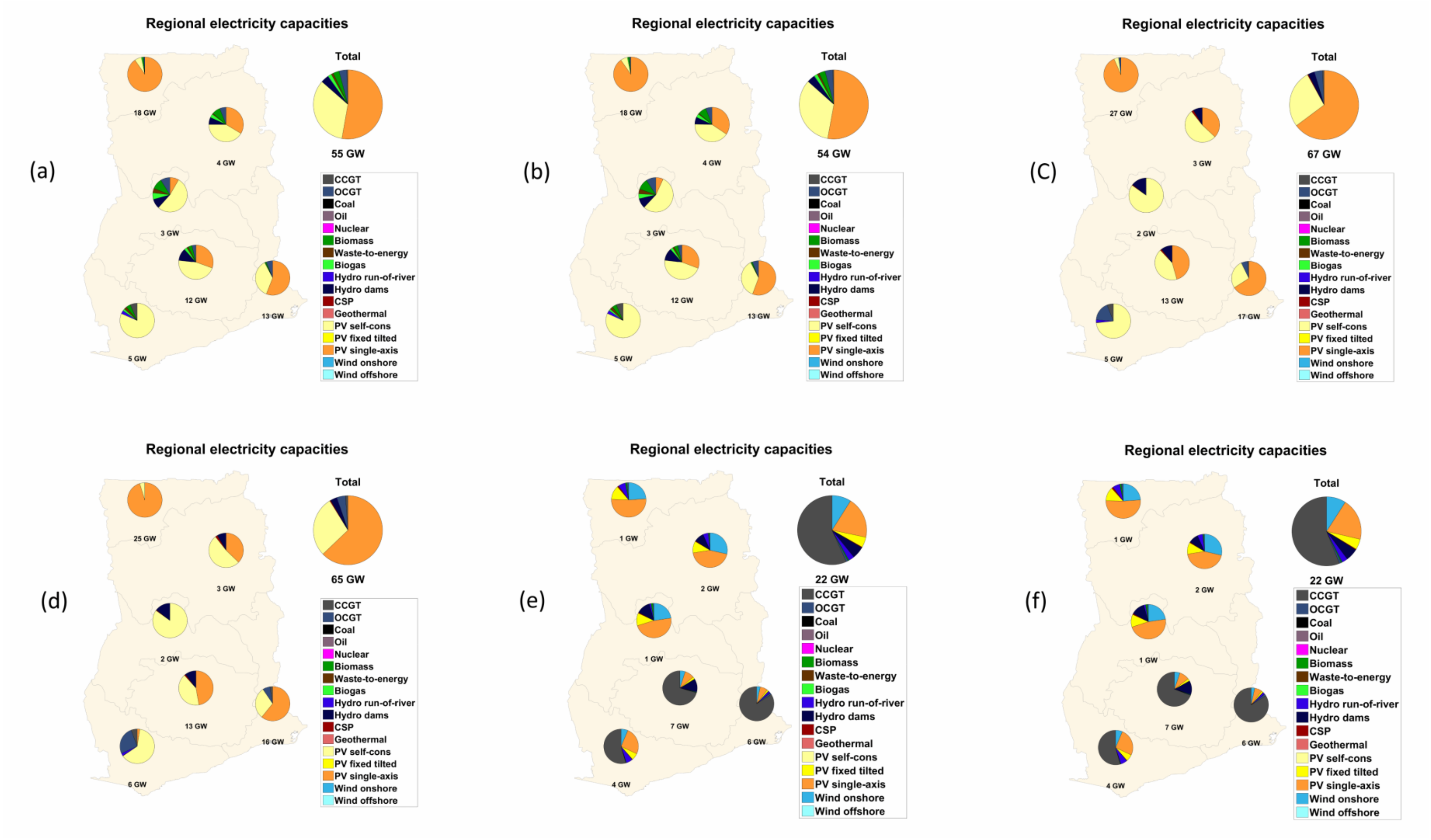


Figure A9: Regional electricity installed capacities for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

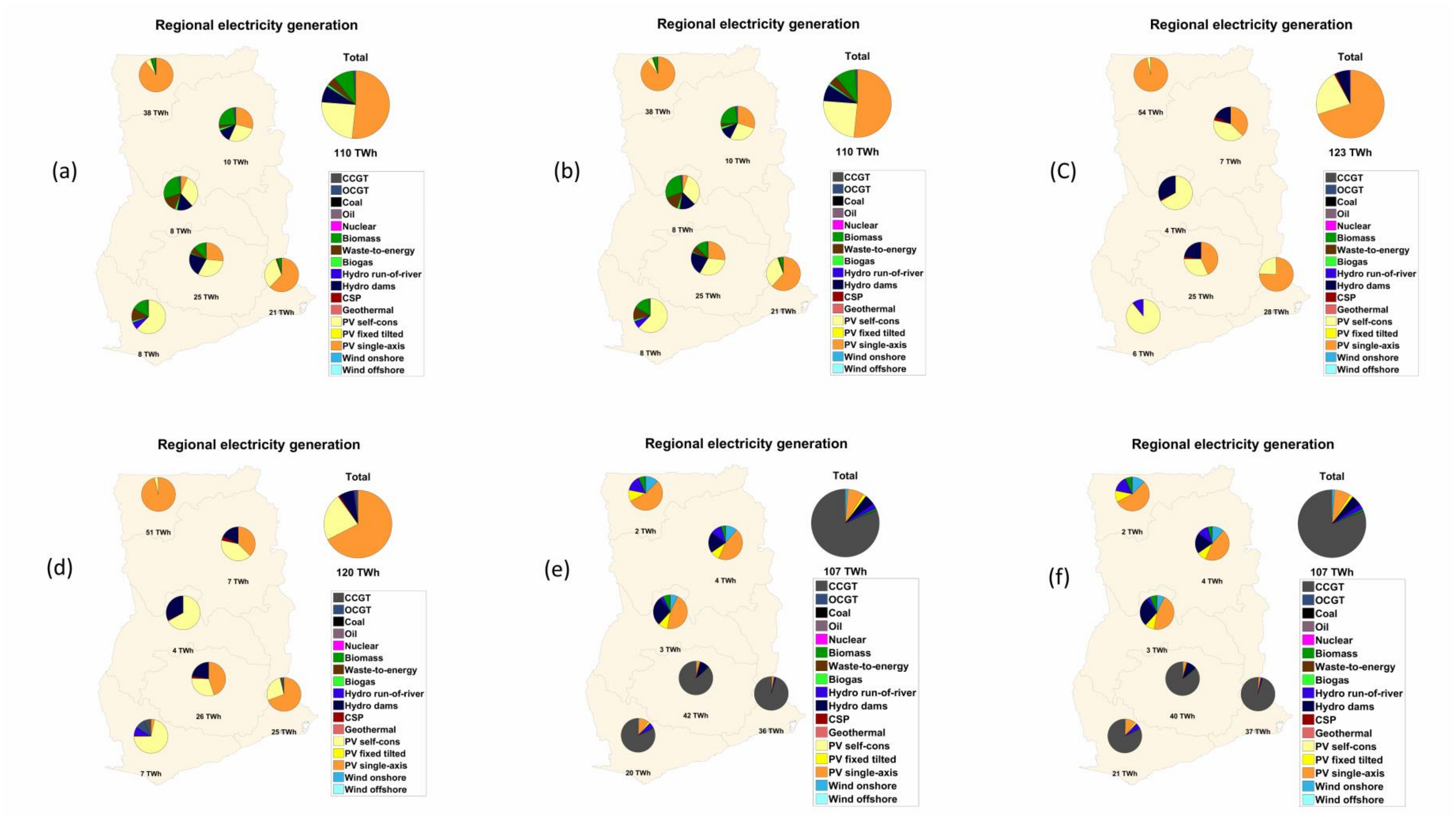


Figure A10: Regional electricity generation for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

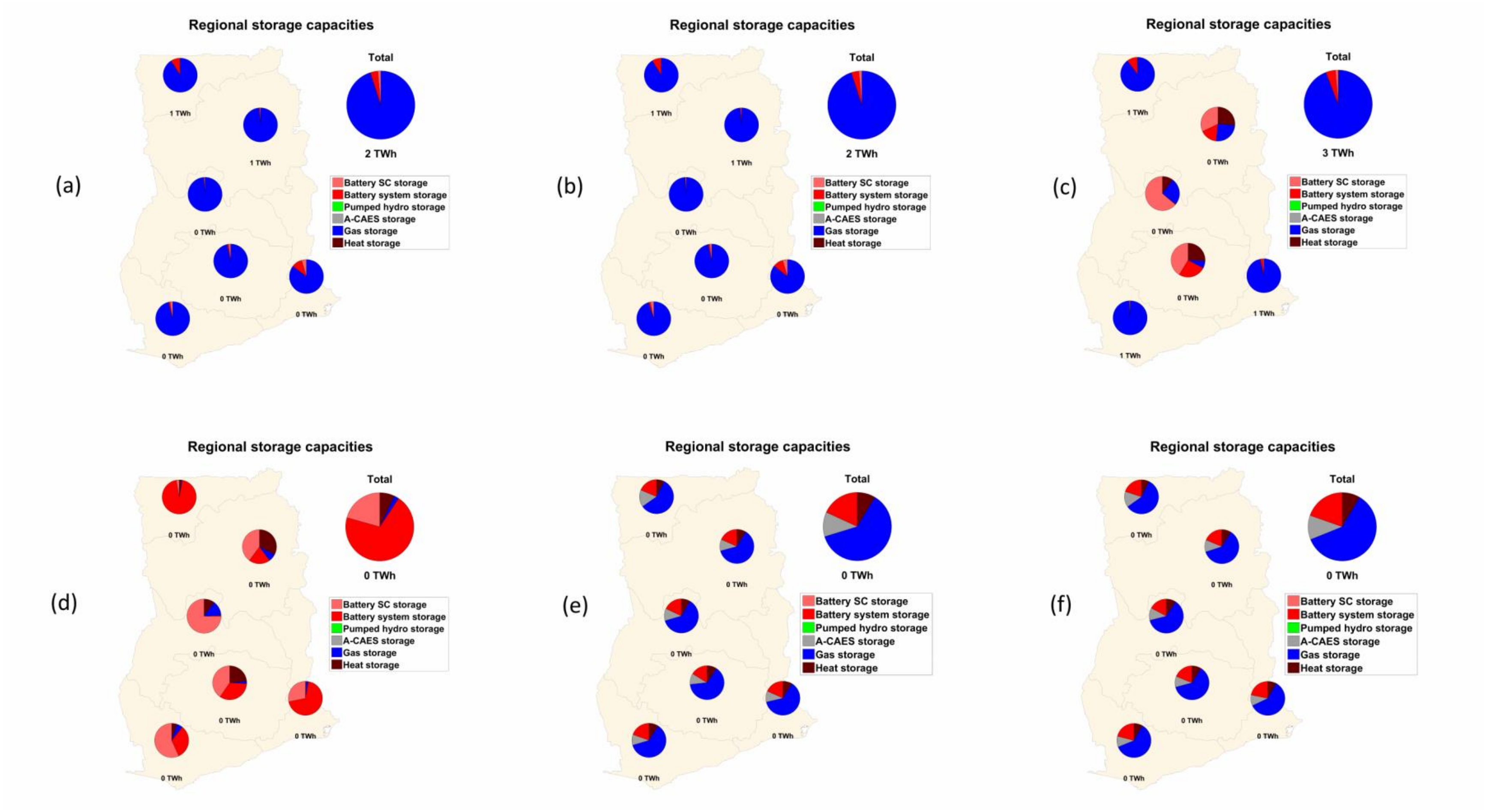


Figure A11: Regional storage installed capacities for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

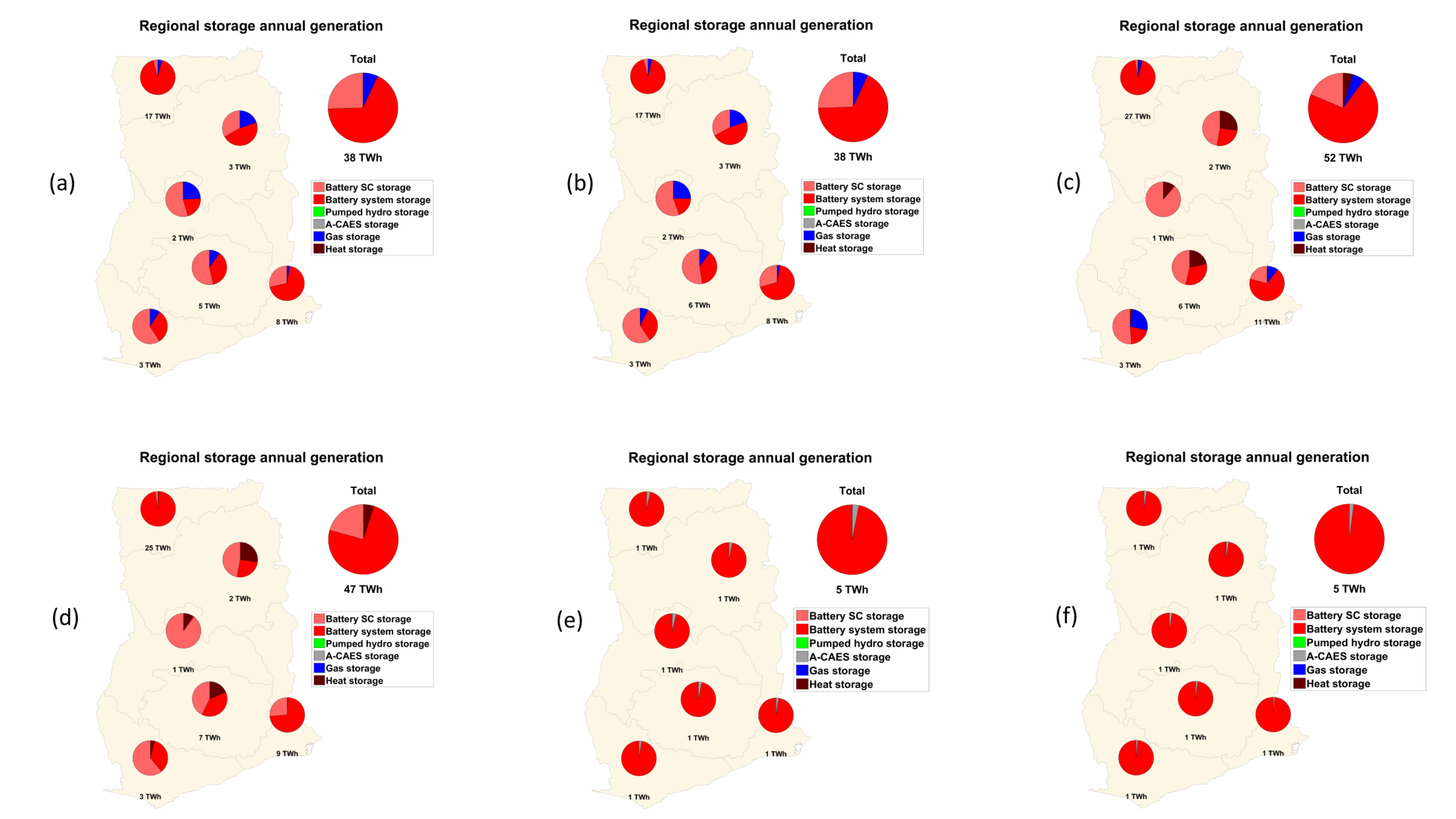


Figure A12: Regional storage generation for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the year 2050.

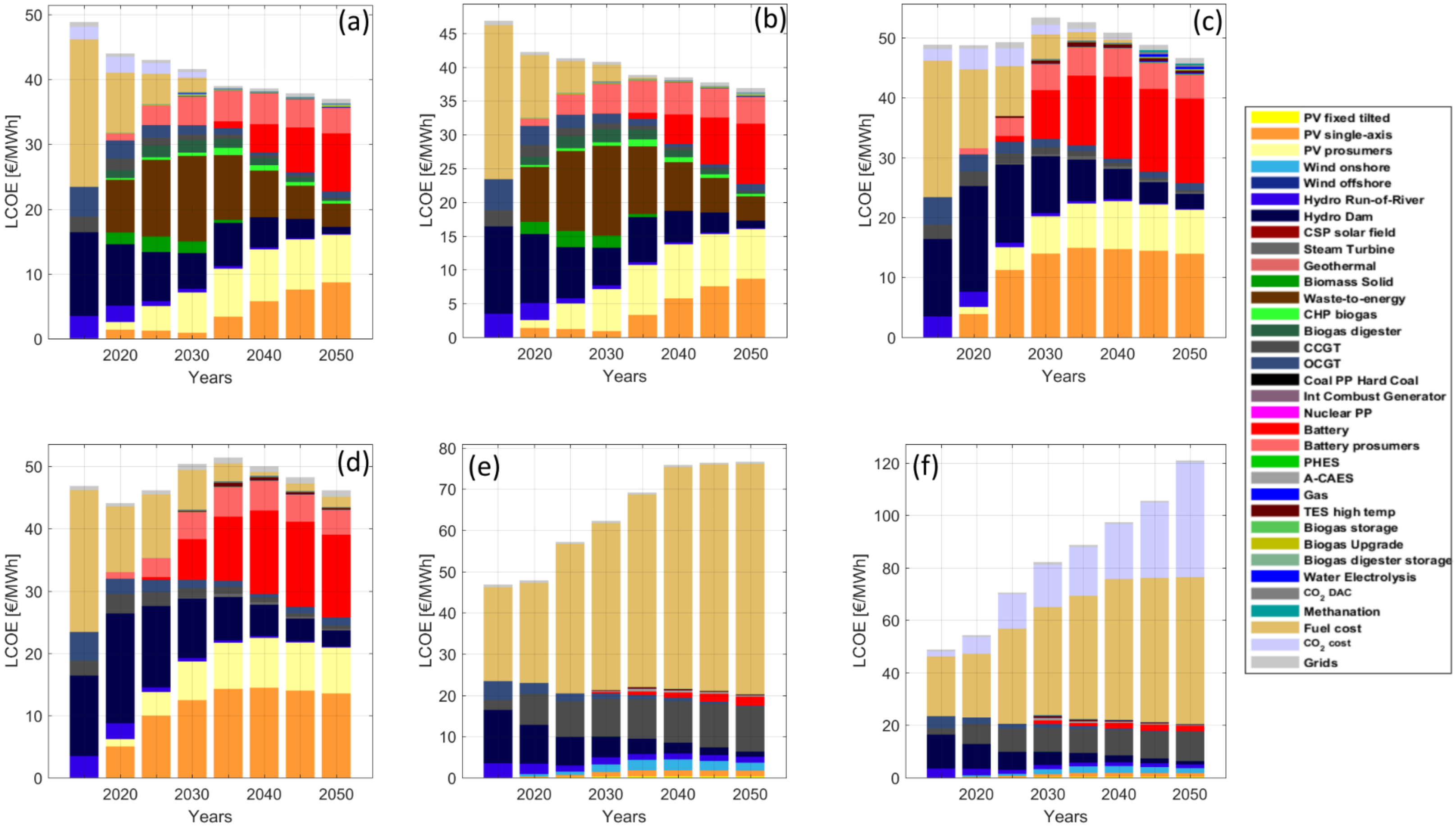


Figure A13: Levelised cost of electricity by technologies in the scenarios BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) from the years 2015 to 2050.

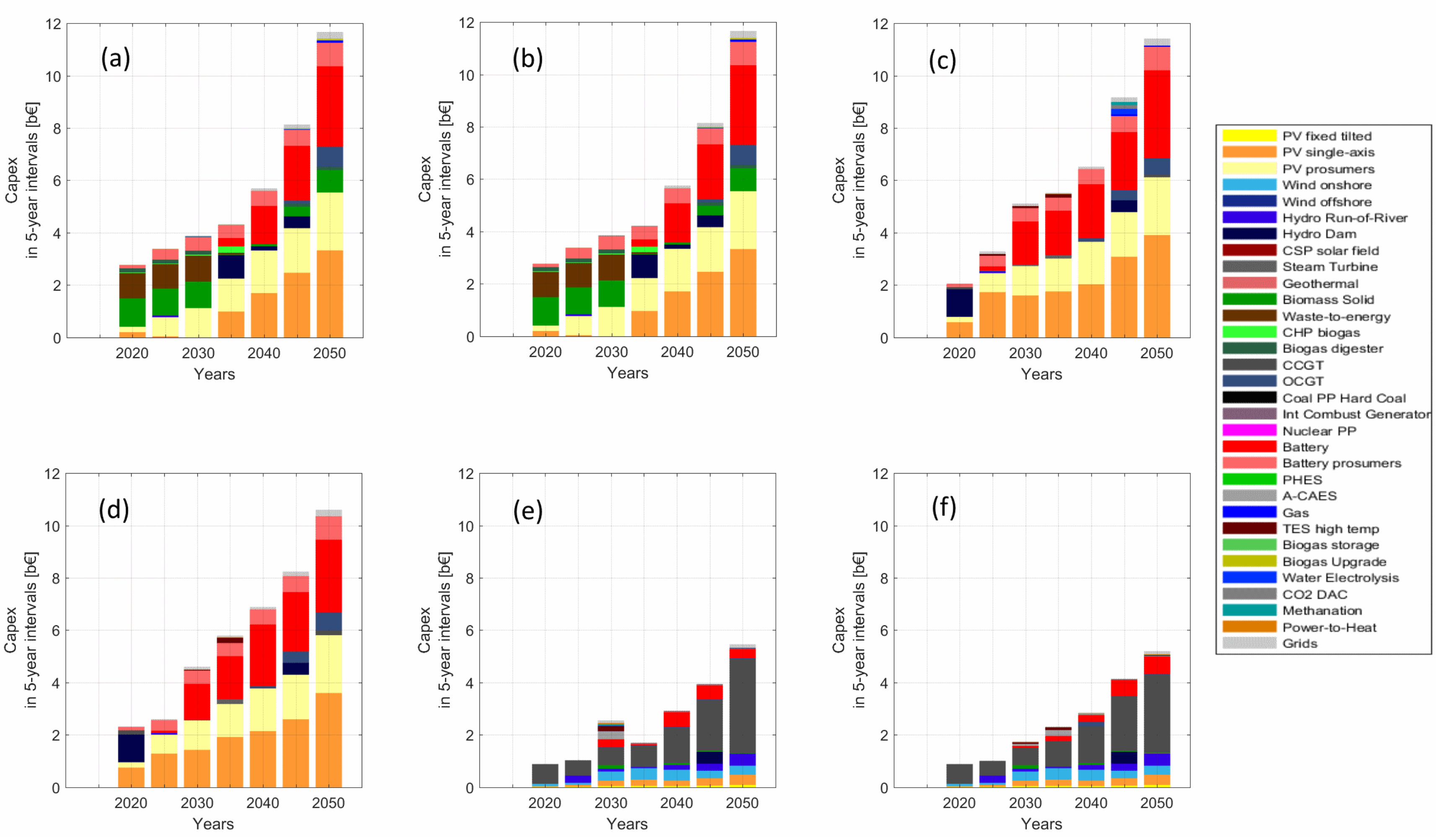


Figure A14: Capex in new generation for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the years 2015 to 2050.

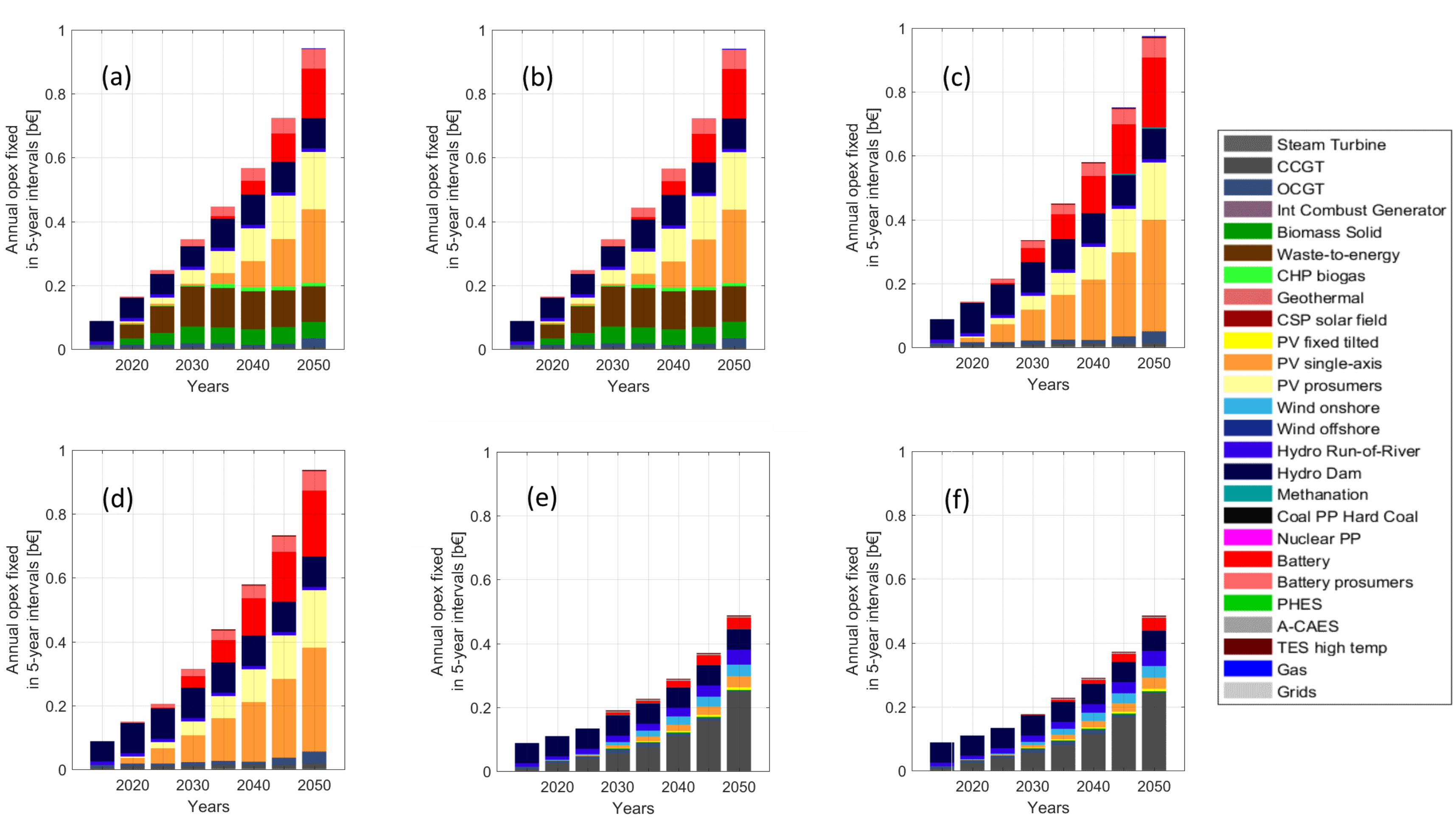


Figure A15: Fixed operational expenditures for 5-years intervals for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the years 2015 to 2050.

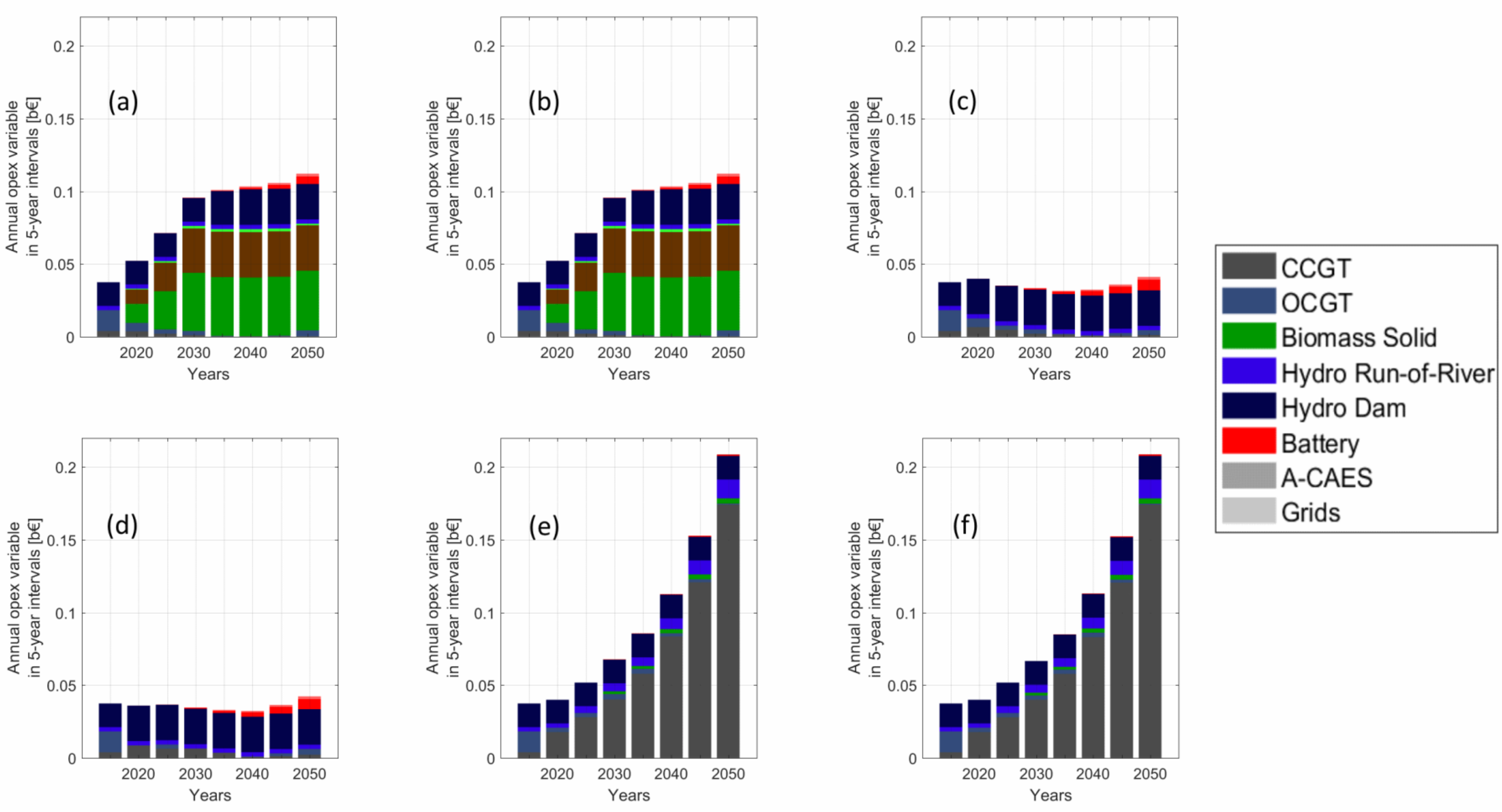


Figure A16: Variable operational expenditures for 5-years intervals for the BPS-1 (a), BPS-1noCC (b), BPS-2 (c), BPS-2noCC (d), CPS (e) and CPSnoCC (f) for the years 2015 to 2050.

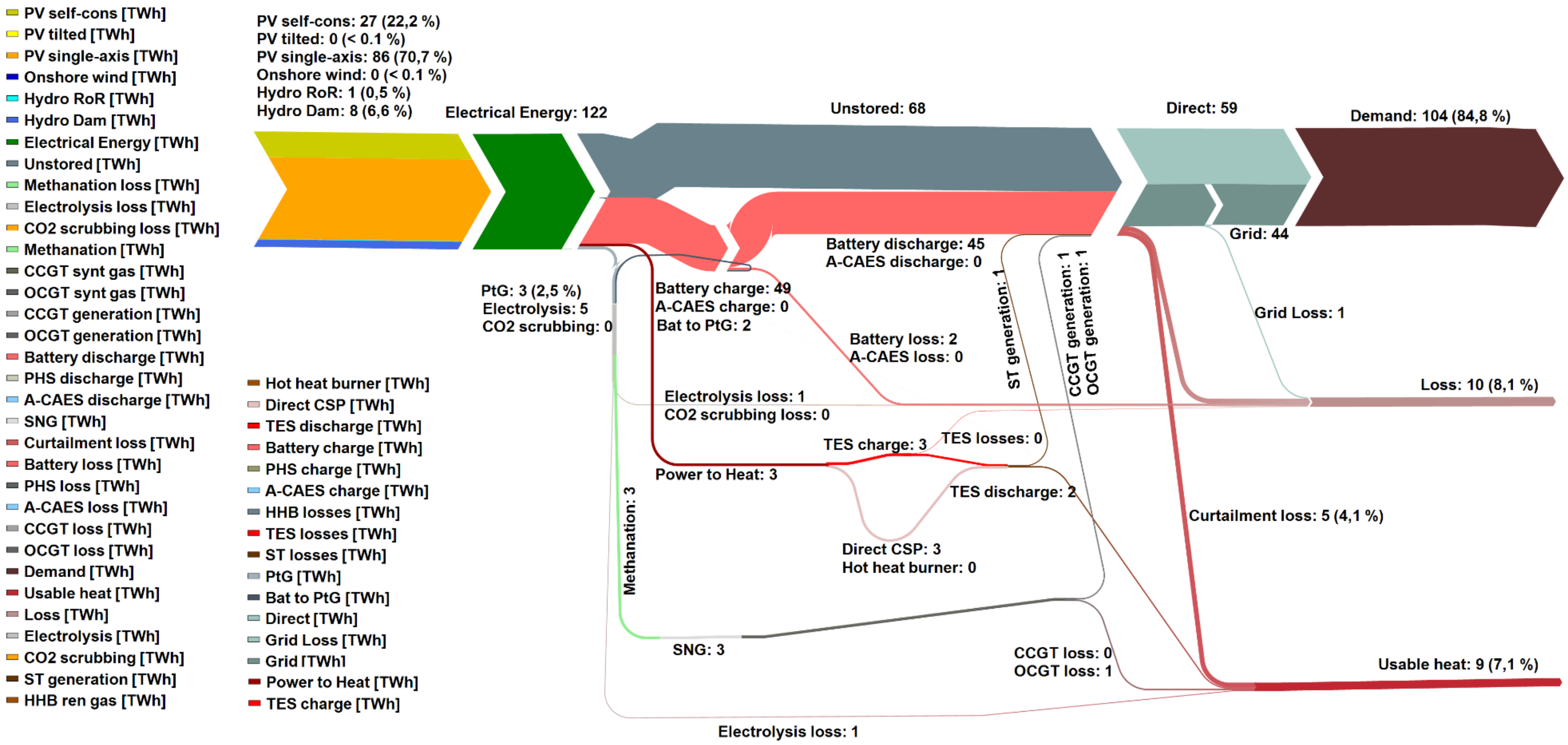


Figure A17: Energy flow of the power system for the BPS-2 in the year 2050.

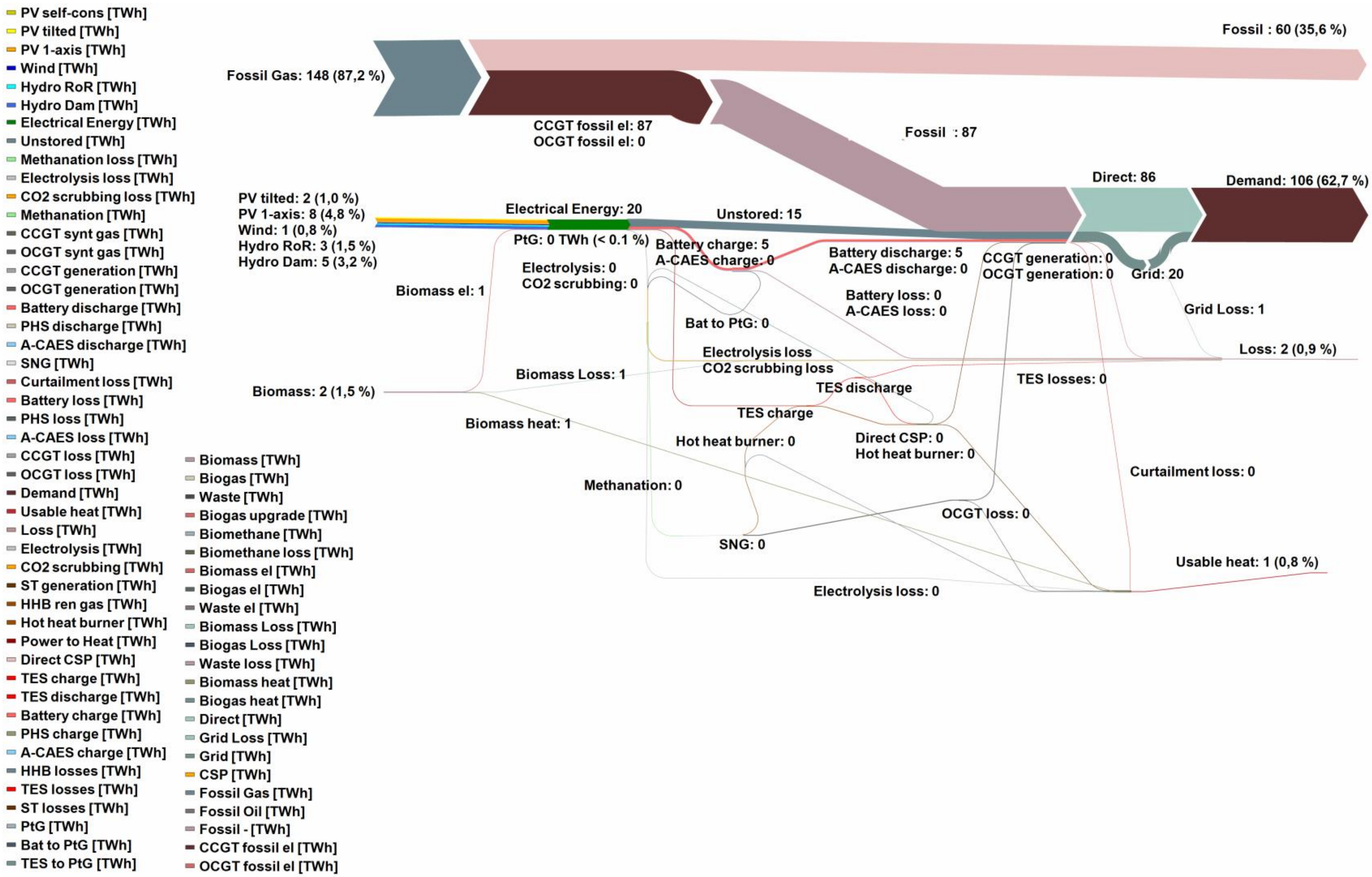


Figure A18: Energy flow of the power system for CPS in the year 2050.