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Long-term electricity generation analysis and policy implications – the case of Ghana

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Abstract: The pursuit of a cost-effective and low-carbon electricity generation environment is critical to achieving Ghana's economic and industrial ambitions. Ghana's development agenda calls for an average electricity consumption of about 5,000 kWh per capita by 2030. To this end, the effective harnessing of energy resources requires the implementation of robust policies for sustainable electricity generation. This study employs the IAEA MESSAGE analytical tool to conduct a quantitative assessment of electricity generation in Ghana from 2020 to 2048. The findings show that, by 2048, a diversified electricity generation scenario will result in a 32.30% decrease in cost and a 55.27% reduction in CO_2 emissions, compared to an accelerated economic growth (AEG) scenario, which will increase cost and CO_2 emissions by 12.21% and 21.10%, respectively. The results underscore the importance of ensuring that electricity generation policies balance economic, environmental, and social concerns. Achieving a green energy transition agenda in Ghana and other developing nations will require a long-term commitment to a generation mix that is both sustainable and economically viable. The implementation of such a policy will require an informed and dedicated effort from all stakeholders.

Mark Amoah Nyasapoh

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PUBLIC INTEREST STATEMENT

Ghana's economic and industrial ambitions rely on a cost-effective and low-carbon energy mix to achieve a per capita electricity consumption of 5,000 kWh by 2030.A well-diversified electricity generation system can lead to a sustainable and cost-effective generation mix, ensuring long-term supply security.The proportion of CO_2 emitted by the energy sector will best be curtailed in the long-term with higher penetration of renewables and low-carbon sources, such as nuclear power.To achieve an electricity generation mix that includes coal, a careful evaluation of environmental impacts and costs will be necessary, as coal consumption will account for 70.7% of the energy mix, compared to 29.3% for gas by 2048.Energy policy implementation must be guided by a commitment to sustainable long-term electricity generation mix.

Subjects: General Systems; Systems Engineering; Design; Power & Energy; Statistics for Social Sciences

Keywords: energy mix; energy resource; MESSAGE model; cost-effective generation; CO_2 emissions; optimization; energy planning; energy modelling; energy transition

1. Introduction

Energy resource scarcity and policy implications for electricity generation have affected the delivery of electricity generation in many countries (Debrah et al., 2020; Victor, 2005). Besides, electricity generation for economic development needs to satisfy social and environmental dimensions of sustainability (Bilgen & Sarıkaya, 2018). However, different countries have different energy resources and consequently different opportunities to generate electricity to meet demand (Nyasapoh, Debrah, et al., 2022). Ultimately, the best electricity supply strategy for such countries usually involves a mixture of energy sources depending on the availability and non-availability of resources (Lucy Shaw, 2018). Even so, Ghana's electricity sector faces the challenge of upfront capital costs and environmental issues related to the country's long-term development plan (Nyasapoh, 2018). However, being sure of electricity demand, generation in a sustainable manner has been a challenge over the past three decades (Debrah et al., 2020; Eshun & Amoako-Tuffour, 2016; Kumi, 2017).

Ghana in 2019 achieved a gross domestic product (GDP) per capita of $2,212 (Ghana Statistical Service, 2020a), a 2020 population of about 30.96 million (Ghana Statistical Service, 2020b). Above all, Ghana aims to attain a full middle-income economic status by 2030. Hence, the projected population and economic growth rates are expected to cause electricity consumption per capita to grow from the current 534 kWh per annum (Energy Commission Ghana, 2021) to about 5,000 kWh per annum by 2030 (Ministry of Energy Ghana, 2019). Recognizing that electricity generation must agree with the goals of Sustainable Development Goals (SDGs) (MESTI, 2020; Republic of Ghana, 2019; UNDP in Ghana, 2020), Ghana signed the SDGs and the Paris Agreement in 2015 and 2016, respectively. Furthermore, Ghana's Fourth National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) in 2020 envisaged a transition of the country's electricity generation to a mix of hydropower, natural gas, renewables and nuclear power by 2030 (Ghana, 2020). Additionally, the Energy Policy envisages that the growing demand for electricity is met with an integrated cost-effective and sustainable planning system (Ministry of Energy Ghana, 2019).

According to international commitment, Ghana's contribution to national development of the energy sector led to several reforms, policies and interventions for sustainable electricity generation (Ministry of Energy Ghana, 2010). As a result, the country transitioned from stand-alone electricity supply systems made up of diesel generators to the hydropower phase of the Akosombo dam. The most current additions are the thermal supplements powered by either gas or light crude oil and finally with the inclusion of some renewable sources (Aryeetey, 2005; Eshun & Amoako-Tuffour, 2016; Gyamfi et al., 2015; Kumi, 2017). Today, the national electricity access rate stands at 85.33%, placing Ghana as one of the countries with the highest electricity access rates in sub-Saharan Africa (Energy Commission Ghana, 2021). Therefore, Ghana's total installed electricity capacity in 2022 is 5,481 MW, with the thermal share being 3,753 MW (68.47%), hydropower 1,584 MW (28.90%) and 114 MW (2.63%) from renewables (Ghana Energy Commission, 2022). However, the amended renewable energy bill redefines hydro as a water-based energy system that produces electricity (Ministry of Energy, 2020), placing all installed renewables at 1,639 MW (30.99%) (Energy Commission Ghana, 2021).

Despite the improvement in the country's electricity sector, the loss in economic activity resulting from the power crisis within the last decade was estimated annually from 1% to 5% of GDP (Cobbinah & Adams, 2018; Theo-Acheampong, 2016). Moreover, Ackah (2015) revealed that Ghana lost on average production worth about US$ 2.1 million per day (or US$ 55.8 million per month) through the last decade's power crisis alone. In addition to the economic challenges of the power sector, the increase in emissions in the Ghana energy sector is highly attributed to the use of liquid fuels in thermal power plants, leading to an increase in greenhouse gases (GHGs), causing climate change (MESTI, 2020; Republic of Ghana, 2015). The country's 2019 National Inventory Report (NIR), submitted to the UNFCCC, discovered that the energy sector contributes about 35.63% of the total GHGs of 42.15 $MtCO_2e$. The 35.63% of the energy sector emissions ranks the sector as the second-largest emitter in Ghana (EPA, 2019). USAID (2016) indicated that about 19% of the GHGs in the energy sector emanate from electricity generation.

Thus, clean electricity generation and its efficiency are based on environmental concerns and goals of sustainable economic development (Wall et al., 1992). Hence, the ambition to exploit energy resources for optimal electricity generation with the dual objective of a cost-effective and environmentally friendly manner (Ministry of Energy, 2019). Thus, the need to incorporate climate change into energy sector policies (Ben Hagan, 2015). As such, the National Climate Change Policy (NCCP) aims at scaling up Ghana's electricity sector with renewable energy penetration by 10%. The NCCP also projects to double the energy efficiency in power plants by 20% by 2030 (MESTI, 2013). However, the Renewable Energy (Amendment) Bill, 2020 has included all hydro energy systems as renewables (Ministry of Energy, 2020). Even though renewable energy sources have had a low pace of penetration in Ghana's energy mix (Nyasapoh, Elorm, et al., 2022). Furthermore, the amendment bill has included nuclear energy as part of clean energy alternatives for Ghana (Ministry of Energy, 2020). Besides, Ghana's Energy Policy proposed expanding electricity generation capacity using nuclear and clean coal technologies to ensure long-term supply security due to the projected uncertainty of domestic natural gas resources after 2030 (Ministry of Energy Ghana, 2019).

Consequently, the importance of energy planning (Demirbas, 2007) is essential to tackle the challenges of resource optimality and electricity generation system (Houri Jafari et al., 2016). Hence, addressing the energy sector challenges for sustainable development requires an effective energy system modelling for policy decision making (Neamtu & Neamtu, 2017). Therefore, there is increasing interest in the use of energy modelling tools and techniques (Utlu & Hepbasli, 2006) for the assessment of the power system to achieve long-term security of supply (Augutis et al., 2016).

Based on the study by Ouedraogo (2017b), several energy sector assessments have been made to influence policy decision making for sustainable energy solutions. Among the key reasons for developing energy models are energy system optimality, oil price volatility, and climate change concerns. For example, the study by Esmail and Cheong (2021) applied the MESSAGE tool for the optimal long-term generation strategy for Saudi Arabia. The study revealed that a mix of electricity generation with the inclusion of advanced traditional thermal plants, nuclear and renewable technologies, mainly solar and wind, will serve as a sustainable and competitive mix of generation for Saudi Arabia (Esmail & Cheong, 2021). Ouedraogo (2017a) through the Long-range Energy Alternative Planning (LEAP) model, a system-based approach to the African energy system was analysed. The study concluded that high greenhouse gas emissions and supply shortages will be prevalent in the African energy sector by 2040, as a result of the increase in fossil fuel consumption (Ouedraogo, 2017b). Seck and Toba (2019) used a tree-like exploration methodology to assess future grid development strategies in West Africa. A methodology that was said to enable a clear examination of the long-term effects of decision-makers and also for the observation of system responses to the so-called decisions (Seck & Toba, 2019). In a recent study, (Nyasapoh, Gyamfi, et al., 2022) revealed that a novel alternative to the future of clean energy solutions for West Africa can be a hybrid energy system of nuclear and renewables. Thus, an alternative to the growth of small and medium-scale industries (Nyasapoh, Gyamfi, et al., 2022).

The Ghana Energy Commission (Energy Commission Ghana, 2006) developed the Strategic National Energy Plan (SNEP I) for a sound energy market by formulating a comprehensive plan to identify the optimal development path. As a result of the challenges in the energy sector that hinder Ghana's development, Abban applied an analysis of the scenario of energy demand, costbenefit and carbon limitation on the path to electricity generation. In particular, it was revealed that the attention to increasing renewable energy in Ghana's energy mix is subject to a resilient environment of the energy sector (Abban & Awopone, 2021). Furthermore, another study was conducted on possible energy solutions for Ghana through analysis of alternative pathways and it was revealed that the policy direction on suitable policies for clean power generation, particularly renewables, will limit CO_2 emissions in Ghana (Awopone, 2017). Through the application of LEAP, Awopone et al. (2017) examined Ghana's power generation plan on renewable energy penetration pathways. The study revealed that the commitment to the country's renewable energy agenda will reduce greenhouse gas emissions and also increase economic benefits of the energy sector (A. K. Awopone et al., 2017b). As part of energy planning, the study by Nyasapoh and Debrah (2020) ascertained the role of nuclear power as a cost-effective and low-carbon energy source for Ghana's climate change mitigation. The study by Nyasapoh (2018) explored a long-term energy supply strategy to ascertain the future sustainability of satisfying electricity demand while maintaining a low carbon environment using the Energy Supply Strategy Model and their General Environmental Impacts (MESSAGE) optimization model. It was revealed that despite the needed research and development in the energy sector, the optimisation of the electricity supply technologies and accompanying fuels is critical for national development (Nyasapoh, 2018). Agyekum (2020) analysed the strengths, weaknesses, opportunities, and threats of Ghana's renewable energy sector with the application of SWOT analysis and concluded that the renewable energy sector is well-positioned for electricity generation. In addition, the study by Abokyi et al. (2019) confirms the adoption of low-carbon energy sources for electricity generation in Ghana will help combat global warming challenges. Furthermore, by simulating conventional and non-conventional energy technologies, the economic and environmental implications of the renewable energy policy were investigated in Ghana (A. K. Awopone et al., 2017a). The review by Asumadu-Sarkodie and Owusu (2016) analysed and created the awareness of Ghana's energy sector strategic planning and policies as an informative tool for decision-making on and utilization of energy resources.

Despite the importance of the studies discussed above, the key limiting factor is the long-term policy implications of Ghana's electricity generation in addition to the generation mix technological proportion. In effect, the paper addresses several gaps in Ghana's electricity generation mix. These include but are not limited to: first, long-term (30 years) electricity supply projection situation together with investment cost and GHG emission implications, compared to Ghana's ever 15 years electricity supply projection, SNEP I (Energy Commission Ghana, 2006). Secondly, the forecast of a fast-growing economy with an electricity generation mix to achieve such high growth is analysed in this study. Lastly, Ghana's electricity supply ambitions (Ministry of Energy, 2010, 2019) are without proportions against the electricity supply projections of the current study. Therefore, Ghana's development agenda is based on the dual objective of generating electricity in a cost-effective and low-carbon environment.

Thus, the article presents a quantitative model-driven analysis of Ghana's energy sources for electricity generation. It brings to fore the policy implications of such generation options on socio-economic development using the Model for Energy Supply Strategy and their General Environmental Impacts (MESSAGE) analytical tool. The paper simulates three scenarios: business as usual (BaU), diversified, and accelerated economic growth (AEG). Each has some form of the electricity generation mix. Additionally, the impact of each scenario on the dual objective of providing electricity in a cost-effective and environmentally friendly manner. Therefore, the paper seeks to contribute to and aid policy decision-making for long-term energy balance planning for Ghana based on current resources and international obligations such as climate change. The paper also projects a long-term electricity supply strategy and implementation that should not be taken for granted based on the triple bottom line of economic growth, social and environmental concerns. Thus, a well-planned mix of electricity generation with low carbon technologies will help to achieve key global protection and socioeconomic development initiatives and programs enshrined in SDGs 7 and 13. Finally, the paper immensely contributes to the literature in energy systems modelling and planning.

1.1. The energy transition agenda

Energy transition is a pathway toward the transformation of the global energy sector from high-emitting or fossil-based fuels to zero carbon by the second half of this century (IRENA, 2022). Thus, bottom line of the current global energy transition agenda is to reduce energy-related CO_2 emissions to limit climate change. The transition to a climate-neutral economy to ensure green energy transition saw the European Union engaged in energy, climate and infrastructure policy developments (Simson & Santos, 2022). A more recent debate centered on the inclusion of nuclear and natural gas as part of the green energy solutions to combat climate change (European Parliament, 2022). Based on the European scenario, the study by Sarrica et al. (2016) discovered that the path to energy transitions calls for cohesive multiple theoretical, disciplinary and methodological perspectives research.

Thus, the state-of-the-art energy transition processes include a variety of technologies and approaches that are being developed and implemented to reduce reliance on fossil fuels and increase the use of renewable energy, energy storage, smart grids, carbon capture and storage (Slattery, 2015). Such technologies and approaches are being used in various combinations to create a more sustainable energy system that is cleaner, more efficient, and more resilient to the impacts of climate change (Kabeyi & Olanrewaju, 2022).

The study by Sovacool (2016) investigated the issue of time in global and national energy transitions with recognition analysis of causal complexity. It was discovered that the method for sustainable energy transition is not enchanted but a well-planned and effective implementation (Sovacool, 2016). Therefore, Smil (2010) revealed that despite the natural gas potential of the United Kingdom and the Netherlands, the former could not nurture the energy switch compared to the latter (Smil, 2010).

The debate on Latin America’s energy transition surrounds the reconciliation of regulations with climate and energy policies to ensure the sustainable elimination of fossil fuels (Simson & Santos, 2022). Thus, the Southern American energy transitions hinge on energy efficiency and generation with regional development on the implementation of sustainable energy transition programs and regulations (Ise et al., 2020). Furthermore, the greener energy matrix for Latin America in the study by Stanley (2022) indicated that the energy transition is accompanied by long-term but uncertain consequences for the national economies. Therefore, the reduction of risk for these countries requires a long-term strategic vision to face challenges (Stanley, 2022). The enactment of Energy Transition Law No. 2099 and Bill 365 for Colombia offers opportunities for renewable energy investment and green energy transition (Gomez, 2022). The study conducted for the Galapagos Islands revealed that the sustainable energy transition by 2050 requires first the effective allocation of economic resources and legal actions (Icaza-Alvarez et al., 2022).

Particularly, the energy transition in South America refers to the shift from a primarily fossil fuel-based energy systems to one that relies more on renewable energy sources. This process is being driven by several factors, including concerns about climate change, the need to reduce dependence on fossil fuels, and the desire to promote economic development (Nadaleti et al., 2022). For instance, the energy transition processes in South America just like any other continent are ongoing and vary by country with significant trends and developments in electric vehicles, energy efficiency, smart grids, nuclear energy, biomass and biofuels (Gielen et al., 2019; Kabeyi & Olanrewaju, 2022). Even though Ecuador relies more on oil exports for revenue (Espinoza et al., 2019), the country’s energy transition agender has an ambitious renewable energy targets and steps to promote a more sustainable energy system (Icaza et al., 2022). Despite the early stages of the Peru energy transition process the country has set ambitious renewable energy targets with steps to promote a more sustainable energy system (Phan, 2020; Velarde, 2022). The work by

López et al. (2020) showed some insights into the energy transition agenda mainly solar on Chile, Peru and Colombia. It was revealed that Chile is expected to achieve 2,000 MW in 2018, whereas the neighbouring Peru has 201 MW, at least twice as much installed PV capacity. On the other hand, one percent of Colombia's total installed PV capacity, or an estimated 165 MW, was located in non-interconnected regions in 2015 (García et al., 2013).

For instance, in order to fulfill its commitments under the Paris Agreement and combat climate change, South Africa must make the transition away from fossil fuels (Todd & McCauley, 2021). The majority of experts classify Africa as a continent with abundant untapped energy potential, placing it in a good position to provide the necessary energy using more environmentally friendly and renewable means (Adulugba, 2021; Manjong et al., 2021). The "Desert to Power" initiative takes a comprehensive approach to providing solar energy to the Sahel region. Thus, on-grid and off-grid generation are combined in Desert to Power (AfDB, 2021).

Ghana's energy transition agenda has hinged on the efforts to address climate change through tangible climate actions for more than a decade now. In this regard, Ghana published its national climate change policy in 2012, a low carbon development strategy in 2015, ratified the Paris Agreement in 2016 and has already started implementing the measures in the nationally determined contributions (Ghana, 2020).

Above all, the quest for greener economies and a sustainable energy mix reinvigorated the energy transition agenda to ensure the transitions for a sustainable environment and social well-being (García-García et al., 2020).

2. Methodology

The study's methodology is built around the Model for Energy Supply System Alternatives and their General Environmental Impacts (MESSAGE) analytical tool to analyse electricity demand projections for Ghana. The MESSAGE optimization model (IAEA, 2016; Messner, 1997; Schrattenholzer, 1981) was used to evaluate electricity supply in Ghana. The major function of the tool is to balance the demand for final electricity use through the use of conversion technologies. The MESSAGE Model is based on Linear Programming and can utilize mixed-integer options to optimize the cost objective function. The MESSAGE model optimizes an objective function under constraints that define the possible region containing all potential solutions to the problem.

2.1. Message mathematical model

The MESSAGE model is a dynamic linear programming tool that minimizes the objective function, the net present value of the overall electricity system (Messner, 1997). The objective function used in the minimization process is presented as Eqn. 1.

$$min \sum_j \sum_{t=1}^{T} [d_t^o \Delta_t X_{jt} * i_{jt} + d_t^c \Delta_t Y_{jt} * O_{jt}] \quad (1)$$

Where;

T : the number of periods in the model

j and t : technology and period, respectively

d_t^o and d_t^c : discount factors applied for operating and capital costs, respectively

Δ_t : Length of period t in years

X_{jt} : fuel consumption of technology j in period t

Y_{jt} : capacity variables for annual new installation of technologies

i_{jt} : Specific investment of technology *j* at period *t*

O_{jt}: operating cost of technology *j* in period *t*.

The basic dominant equations employed in the electricity system modelling that include the environmental modelling are the electricity demand equation, the electricity (commodity) balance equation, the technology capacity equation, and the environmental impact accounting, a user-specified equation.

The electricity demand equation is specified as Eqn. 2

$$\sum supply \geq Demand$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\eta_{i,j,t}\times x_{i,j,t}\geq D_{i,t} \quad (2)$$

Where$t$: period of study

η: efficiency of plant

x: installed capacity

i: modelling years

j: conversion technology

D: electricity demand

From the electricity demand equation in (2), the electricity (commodity) balance equation can be formulated as,

$$\sum Production - \sum^{C} onsumption \geq 0$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\eta_{i,j,t}\times x_{i,j,t}-\sum_{v=1}^{V}x_{v,i,t}\geq 0 \quad (3)$$

Furthermore, the installed capacities are described by the technology capacity equation presented as Eqn. 4

$$\eta_{T}\times{}_{T}-\sum_{t=1}^{T-1}\pi_{t}\times y_{t}\leq\pi_{T}+Y_{0} \quad (4)$$

WhereY_0: historical capacity
y: new installations

π: plant factor

Accounting for environmental impact is given by employing Equation 5

$$\text{Upper Limit} > \Sigma(EFi * FUELi) > \text{Lower Limit} \quad (5)$$

Where *FUELi*: Fuel used by conversion technology i

EFi: coefficients with which technology is entering a relation

The *EFi* in (5) is defined as

$$EFi = CEF \times \frac{44}{12} \times Oxydationfacor \times 8.76 \times 3.6/1000 \quad (6)$$

Where *CEF* is the Carbon Emission Factor. The values of various fuels *CEF* and their oxidation factors are obtained from the Revised 1996 IPCC Guidelines for national greenhouse Gas Inventories: Workbook.

The investment costs of power plants are considered the dependent variable required per kW specific value in the model. These costs are multiplied by the annual new installations of the technology to yield the overall cost of investment. The investment cost of technology is expressed in Equation 7:

$$\sum_{t=1}^{T} d_t \Delta_t Y_t * i_t. \quad (7)$$

Where;

d_t : Discount factor for period *t,*

Y_t : Annual investment in period *t,*

Δ_t : Number of years in period *t,*

i_t : Specific investment cost in period *t*, and

T : Number of periods in the model.

The annualized cost serves as a useful metric for comparing the costs of power plants every year to measure their relative contribution to the total net present cost. The annualized cost has been computed by first calculating the net present cost, then multiplying it by the capital recovery factor, as shown in Equation 8:

$$C_{am} = CRF\left(i, R_{proj/plant}\right).C_{NPC} \quad (8)$$

where:

C_{NPC}: net present cost [$]

i: annual real discount rate in percent

$R_{proj/plant}$:project or plant lifetime in years

CRF (): a function returning the capital recovery factor

Equation 9 is the electricity demand-supply balance constraint. At the optimal level, the supply of electricity must at least meet the demand. That is:

$$\sum_{j \in Pe} \eta_{jt} X_{jt} \geq \sum_{j \in Ce}^{T} X_{jt} + D_{et} \quad (9)$$

Where;

C_e: energy consumer

P_e: producer of electricity

D_{et}: demand for electricity which is exogenous

η_{jt}: Conversion efficiency of energy technologies

Xjt: fuel consumption of technology j in period t

Equation 9 ensures that all producers of energy carriers (technologies in P_e) supply sufficient electricity for either all consumers (technologies in C_e) or the exogenous demand for e (D_{et}), taking into account the conversion efficiencies of the technologies ($_{jt}$).

As shown in Equation 10, the capacity requirements of energy technologies are determined by a vintage type of approach. Production in a period is related to all capacities up to a certain age of a power plant (technical plant life, $\prod_j$), including capacities existing before the first modelled year (h_{jt}). This illustrates a major constraint to electricity production:

$$\eta_{jt}X_{jt} \leq \alpha_{jt}\sum_{\tau=t-\prod^j}^{t}\Delta_\tau Y_{\tau j} + h_{jt.} \tag{10}$$

Where

$_{jt}$: Conversion efficiency of energy technologies

Xjt : fuel consumption of technology j in period t

α_{jt} : plant factor

$\prod_j$: the technical plant life,

Δ_t : Length of period t in years

Yjt : capacity variables for annual new installation of technologies

h_{jt} : the first modeled year

The plant factor α_{jt} describes the average utilization of the capacity of a power plant. This is usually more important for electricity generation plants than for other technologies.

Equation 11 is the constraint on the overall consumption of resources controlled by the quantities extracted over the entire model horizon from the available resources (R_j). That is:

$$\sum_{t=1}^{t}\Delta_\tau X_{jt} \leq R_{j.} \tag{11}$$

Where

Δ_t : Length of period t in years

Xjt : fuel consumption of technology j in period t

R_j : available number of resources

2.2. Electricity demand projections

The MESSAGE model that estimates electricity supply requires a corresponding electricity demand that will serve as the exogenous input variable for the model (Rao et al., 2008; Scire et al., 2000). Hence, the study employed the electricity demand projections made by the Energy Commission of Ghana using the Long-range Energy Alternatives Planning (LEAP) model. The demand projections are based on two scenarios: Business-as-Usual (BaU) and Accelerated Economic Growth (AEG) (Energy Commission Ghana, 2019). The BaU scenario is based on the average performance of the Ghanaian economy over the past decade. On the other hand, the AEG scenario considers the Ghana Shared Growth and Development Agenda projections that envisage a higher economic growth (Energy Commission Ghana, 2019). Estimates of electricity demand for both the BaU and AEG scenarios ended in 2030. Following the work of Nyasapoh (2018), the current study extrapolated the data to 2048 to suit the "Long-Term National Development Plan of Ghana (2018–2057)" (NDPC, 2016) of the National Development Planning Commission (NDPC) (NDPC, 2016). The NDPC development plan is based on government policies and demographic, macro-economic, and technological factors (NDPC, 2016).

Based on this estimate, electricity demand is projected to increase from 18,542 GWh (1,594 ktoe) and 21,971 GWh (1,889 ktoe) in 2020 respectively for the BaU and AEG scenarios at an average annual rate of 5.1% and 8.1% to 30,570 GWh (2,629 ktoe) and 47,926 GWh (4,121 ktoe) in 2048, respectively (Energy Commission Ghana, 2019).

2.3. Electricity supply systems and reference electricity systems

The electricity supply system in Ghana is made up of resources that are converted to primary energy using conversion technologies/power plants. Finally, the primary energy then passes through the secondary level system to final electricity to satisfy demand through transmission and distribution systems (Nyasapoh, 2018). The energy resource, primary and secondary fuel categories considered for simulation and electricity generation are in line with the energy options considered in the Ghana 2019 Energy Policy that aims to achieve a sustainable, all-inclusive, and cost-effective electricity generation system (Ministry of Energy Ghana, 2010, 2019). These included eight fuel options—hydro, natural gas, oil/liquid fuels (i.e., heavy fuel oil (HFO), liquefied petroleum gas (LPG), diesel fuel oil (DFO), light cycle oil (LCO) and gasoline), solar, wind, municipal solid waste (MSW), coal and nuclear power.

For this study, a reference electrical system (RES) was developed based on the Ghana electricity setup or infrastructure. The RES is a framework of energy carriers from one process to the other, starting from the energy resource to the final electricity supply for the consumer (Rečka, 2011; Selvakkumaran & Limmeechokchai, 2011). The RES framework is a process that makes it possible to represent the current energy chain or network, including possible or potential electricity development infrastructure paths for Ghana.

2.4. Electricity generation or supply scenario descriptions

The study developed and simulated three different scenarios to help to provide an effective comparative assessment of the electricity supply in line with the ambitions outlined in the Ghanaian Energy Policy. The policy aimed to develop a long-term, cost-effective and clean electricity generation mix. The three scenarios include BaU, BaU diversified, and AEG.

2.4.1. The BaU scenario

The BaU scenario takes into account the electricity demand projections of the Ghana Energy Commission. Specifically, the scenario considers the electricity supply path in the absence of any major intervention in Ghana's electricity sector. Thus, the BaU includes all existing technologies operating in the country and new ones introduced as committed or potential generation technologies/power plants. All generation technologies under the BaU scenario were modelled without constraints on specified capacities, fuel options, and environmental concerns.

2.4.2. Diversified scenario
The diversified scenario was developed against Ghana's Energy Policy on the backdrop of a well-diversified energy mix for a long-term, cost-effective, and clean electricity supply. The electricity demand for the scenario is the same as the BaU demand projection by the Energy Commission of Ghana. For a well-diversified electricity generation, the scenario was modelled to include all the energy options outlined in Ghana's Energy Policy (i.e., biomass, solar, wind, nuclear and coal technologies). For an all-inclusive generation, technologies/power plants were modelled with constraints such as specified capacity, fuel input and environment.

2.4.3. Accelerated Economic Growth (AEG) Scenario
Through the Energy Commission in 2020, Ghana formulated a Strategic National Energy Plan (SNEP) for a fast-growing economy that ensures a corresponding high electricity demand. However, the electricity generation mix to achieve the high growth in electricity demand has not been analysed. The AEG generation scenario considers the projection of high electricity demand by the Ghanaian Energy Commission. The AEG scenario is based on Ghana's electricity supply path with major interventions in the electricity sector.

2.4.4. Simulation parameters and key assumptions for all scenarios
The BaU, Diversified and AEG supply scenarios were modelled under the following assumptions:

(i) The modelling period comprised 30 years within the "Long-Term National Development Plan of Ghana (2018-2057)" developed by the National Development Planning Commission (NDPC) (NDPC, 2016). The NDPC plan was based on government policies, demographic, macro-economic and technological factors.

(ii) Electricity generation projections span from the base year 2018 to 2048. The year 2018 served as the base year due to the stable electricity system in the country that year.

(iii) In line with Ghana's wind and solar capacity, the study assumed the maximum solar irradiation capacity potential of 6.0 kWh/m^2/day and the wind speed of 6 m/s at 50 m above sea level. This constraint on renewable technologies is to allow for the highest generation capacity for renewable energy sources.

(iv) The electricity system modelling and analysis were carried out based on the overnight cost of all technologies/power plants, the availability of gas resources in Ghana and its imports from Nigeria.

(v) A discount rate of 12% was used to purchase generation technologies or power plants in the country with a 20% reserve margin.

3. Results and discussions
This section discusses the study results, which focus on the options for electricity supply to meet demand projections and the investment cost and the implications of GHG emission for Ghana.

The output values from the MESSAGE model based on the scenarios were first drawn into Excel for the calculation of the figures represented in the discussions. Specifically, five main electricity supply indicators are discussed: installed capacity, generation capacity, fuel consumption, dispatch, and generation cost and emission factors for each of the scenarios. The study first analysis the output for the BaU Scenarios. Subsequently, the analysis of the Diversified and AEG scenarios are the deviations of the output from the BaU scenario. The discussions for all scenarios focus on

2020 to 2048, although the base year is 2018. This is because most of the power purchase agreements in Ghana were established for 2020.

3.1. BaU electricity generation analysis

BaU analysis and discussions serve as the reference case for the study considering the path of electricity supply in the absence of any major intervention in the Ghanaian electricity sector.

3.1.1. Installed capacity

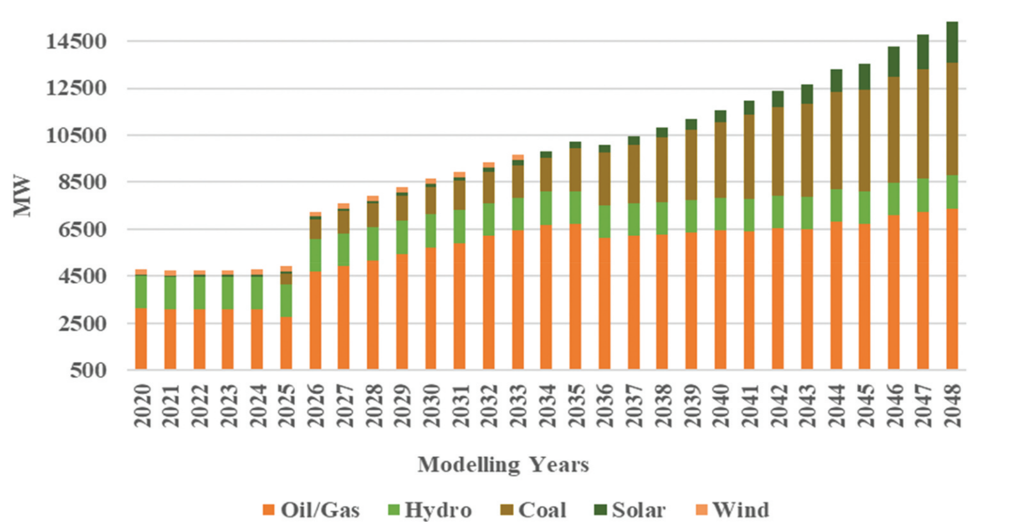
As indicated in Figure 1, the total installed electricity capacity in 2020 is 4,788.11 MW, but will increase to 15,344.56 MW at the end of 2048. This does not include municipal solid waste (MSW) for electricity generation and nuclear technology. Oil/gas technologies dominate installed capacity with a share of 48.15% of total installed capacity at the end of 2048.

Coal technology followed as the second largest installed capacity after its installation in 2025 with 460 MW. Still, coal will increase to 4,816.61 MW at the end of 2048, representing 31.39% of the total installed capacity. Alongside, hydro and solar technologies at the end of 2048 will have installed capacities of 1,395.58 MW and 1,743.87 MW representing 9.09% and 11.36% shares, respectively. On the other hand, wind technology began with a total installed capacity of 225 MW in 2020. The installed wind capacity ended in 2033 with the same installed capacity representing 2.33%.

The expansion in the model's results of the electricity generation capacity is confirmed by optimization studies, such as Awopone et al. (2017), Kichonge et al. (2015) and Nyasapoh (2018). The high share of solar in installed capacity (11.36%) at the end of 2048 is attributable to the suitability of solar technology for both off-grid and grid-tied applications in Ghana (Ministry of Energy Ghana, 2019). This confirms the argument made by (Sareen & Nordholm, 2021), that a well-structured solar energy policy can help facilitate the SDG agenda for a sustainable environmental future.

That notwithstanding, the results indicate that low carbon energy options, more specifically, renewables and hydro installations, are not encouraging following the 2019 Energy Policy draft ambition to have higher penetration by 2030 (MESTI, 2013). Also, the inability of the BaU scenario to install nuclear technology is attributed to the high fixed overnight cost of 5,000 $/MW at a discount rate of 12% despite the technology's advantage to guarantee greater security of supply and non-emission of GHGs (Ministry of Energy Ghana, 2019). Yet, policymakers are emphasizing the

Figure 1. Installed electricity capacity (MW).



inclusion of such options in the supply mix, largely due to environmental considerations, particularly climate change.

Overall, the BaU scenario has maximized fossil fuels' installed capacity, including oil/gas and coal energy sources. Therefore, the dominance of oil/gas on the backdrop of cost-prohibitive exploitation and volatile prices of oil/gas products in addition to concerns about climate change associated with coal, despite the advantage of the latter to guarantee supply security (Ministry of Energy Ghana, 2019).

3.1.2. Generation capacity

Based on the installed capacity for the BaU scenario, the corresponding generation capacity is presented in Figure 2 with the total system demand curve. Overall electricity generation will increase from 2,197.5 MWyr in 2020 to 6,173.2 Mwyr in 2048. At the end of 2048, the percentage shares of each fuel in the electricity generation mix will be 28.28% (1,746.3 Mwyr) for gas, 10.87% (690.9 Mwyr) for hydro, 56.12% (3,464.4 Mwyr) for coal and 4.7%. (291.5 Mwyr) for solar. In general, technologies such as wind and liquid fuels made marginal contributions to the generation during the period considered.

It can be seen that the hydropower generation is equal throughout the period. On the contrary, coal generation will take over the dominance of electricity generation from gas technology in 2039. The significant contribution of coal to the generation mix portrays an energy mix that is in conflict with the objective of the country's energy policy that emphasizes low-carbon energy sources. Also, the energy transition agenda could be delayed with such coal impact on the generation mix. However, it is envisaged that coal plants will have the right fuel quality and technology to minimize environmental impact.

3.1.3. Fuel consumption

Based on the installed and generation capacities, the total fuel consumption of the system is represented in Figure 3. The system will, in 2020, require a total fuel consumption of 89.7 Trillion British Thermal Units (TBtu) but will increase to 377.9 TBtu at the end of 2048. Disaggregation of this figure by technology shows that using gas technologies will increase their consumption from 69.9 TBtu in 2020 to 110.9 TBtu (29.3%) in 2048. Using coal will increase consumption by 30.1 TBtu in 2025 to 267 TBtu (70.7%) in 2048. Overall, technologies that use gas and liquid fuel will see their consumption decline from 100% consumption in 2024 to 29.34% consumption in 2048. The reduction in consumption is mainly attributed to the dominance of coal consumption from 2036 to 2048.

Figure 2. Electricity generation (Mwyr).

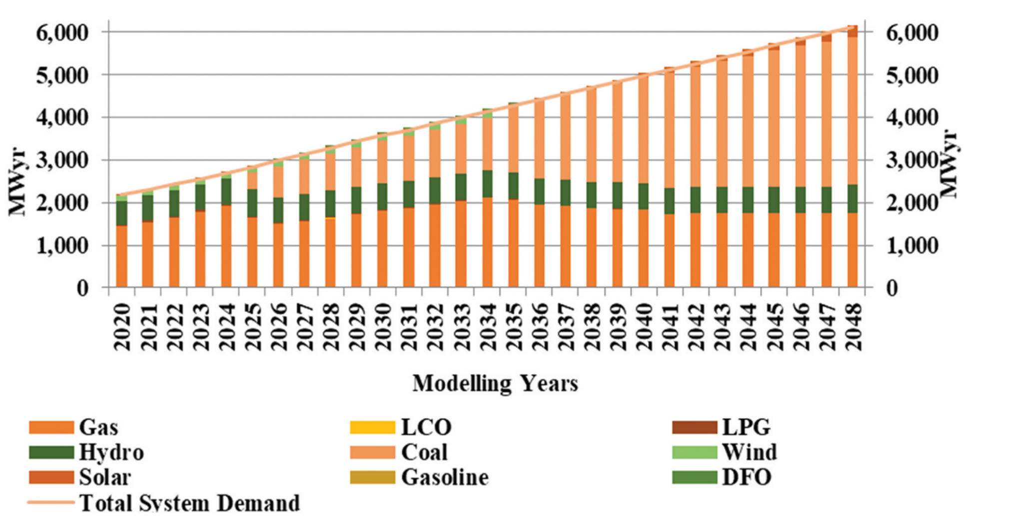
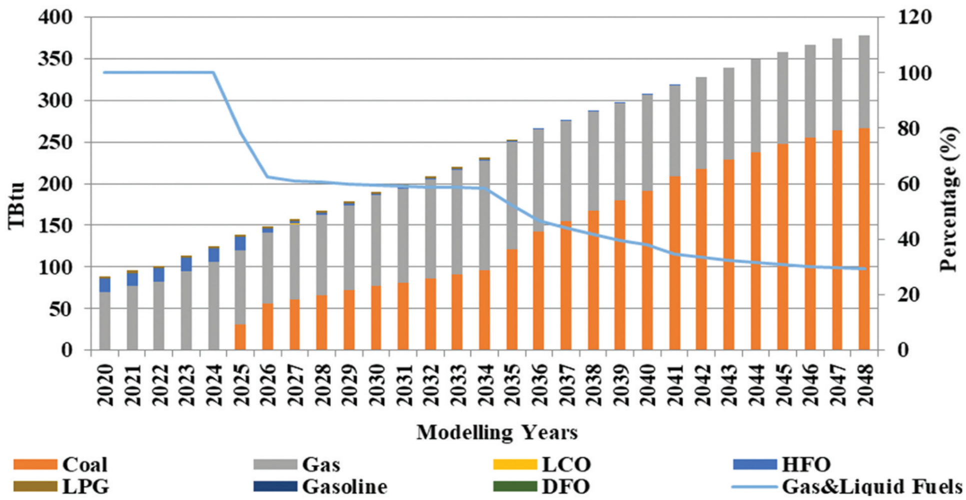


Figure 3. Fuel consumption for electricity generation (TBtu).



By the end of 2048, Ghana will require 70.7% of coal fuel consumption against 29.3% of gas consumption for electricity generation. Hence, an affirmation that energy sector emissions in the future for Africa would rise due to increasing fossil fuel consumption despite low economic development (Ouedraogo, 2017b). Therefore, the study is echoed by Awopone (2017) to ensure the inclusion of clean energy technologies, mainly renewables, for Ghana. Thus, increasing demand for fossil fuels is a development that involves the assessment of environmental impacts and costs on the generation mix. It will also have some macroeconomic implications. Therefore, it exerts pressure on the importation of fuels such as coal with scarce foreign exchange.

3.1.4. Dispatch and generation cost

Electricity generation is accompanied by a cost that is shifted to the final consumer/end-user. The cost/financial implications on the power system are presented as dispatch and average generation costs. The dispatch cost is made up of the electricity production cost. On the contrary, the generation cost considers the capital cost of creating and maintaining the power system on average.

The dispatch and generation cost on average for the system is presented in Figure 4. The total dispatch cost will increase from 142.18 million dollars in 2020 to 604.43 million dollars at the end of 2048, while the average dispatch cost for the entire period will be 364.57 million dollars. However, the average generation cost will increase from 7.39 $/MWh in 2020 to 11.18 $/MWh at the end of 2048. The size of dispatch and generation costs determines the level of tariffs to final consumers of electricity relative to the Energy Policy's ambition to attain cost-effective electricity generation in the long term (Ministry of Energy Ghana, 2019).

As represented in the analysis, Sevim (2016) also asserted that investment in energy supply infrastructure for a sustainable energy future requires long-term strategic planning trends.

3.1.5. Generation emission factor

Figure 5 presents the associated GHGS emissions from electricity generation for the BaU scenario. The emissions are attributed to fossil fuel uses, including gas, LCO, LPG, coal, gasoline, and DFO.

The emissions from electricity generation will increase from 0.21 $kgCO_2/kWh$ in 2020 to 0.51 $kgCO_2/kWh$ at the end of 2048. Gas technology will contribute more to emissions as it will rise from 144.89 MWyr in 2020 to 1,952 MWyr in 2036. By 2037, emissions from coal will dominate, increasing from 2,011.37 MWyr to 3,464.39 MWyr at the end of 2048. Indeed, Ghana may not achieve the aim of the Energy Policy of a cost-effective and low-carbon electricity generation mix

Figure 4. Dispatch and average electricity generation cost.

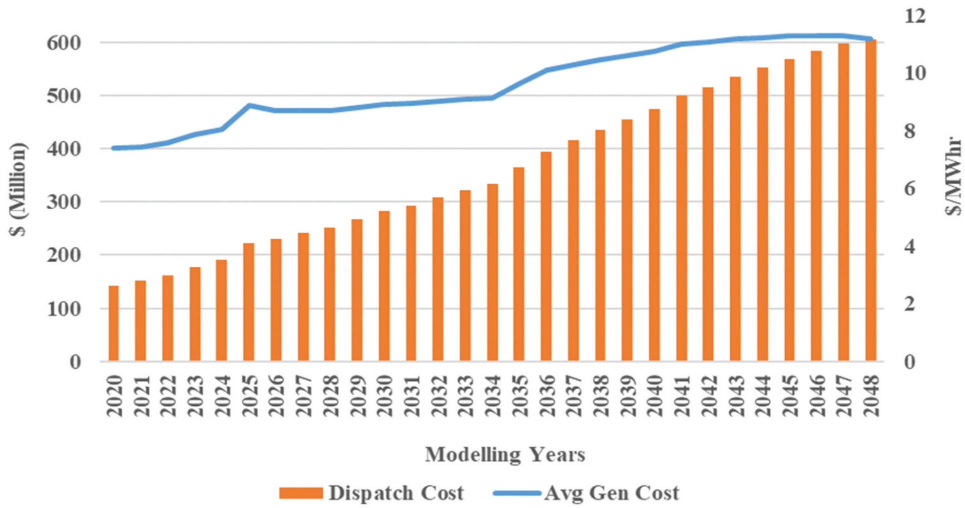
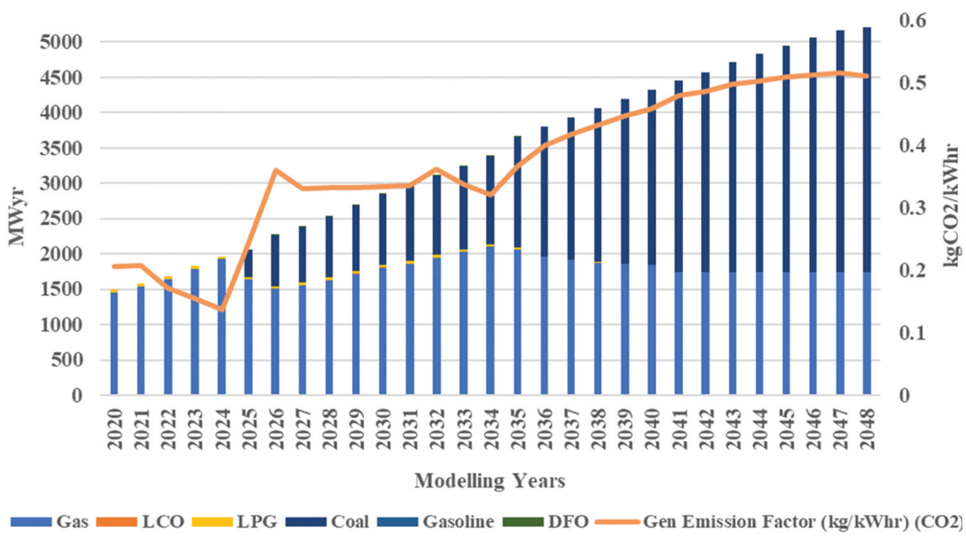


Figure 5. Generation emission factor.



with the BaU scenario due to coal dominance in the generation mix. Clearly, the dominance of coal in the projected electricity generation mix for Ghana is confirmed by Kaygusuz (2009) that coal is responsible for 30–40% of global CO_2 emissions from fossil fuels. However, the study by Seck and Toba (2019) was of the view that policies geared towards a sustainable clean energy future need to be examined through strategic methodologies for the reverse of the assertion by Kaygusuz (2009). In addition, the recommendation outlined by Gurtu and Goswami (2020) proposed a tactical area framework to help minimize CO_2 emissions during the route of socioeconomic development for nations such as Ghana.

3.2. Diversified electricity generation analysis

This section of the analysis of electricity supply is based on a diversification of energy sources and fuel options according to the ambition illustrated in Ghana's energy policy (Ministry of Energy, 2019). To recall, the energy policy aimed at a well-diversified cost-effective and low-carbon energy mix with the inclusion of more renewables and baseload options such as nuclear and clean coal. The diversified electricity analysis reports the margin or deviations of the generation output relative to the BaU.

3.2.1. Installed capacity

The impact of the diversified nature of installed electricity capacity on the system (i.e., 2020 to 2048) is represented in Figure 6. Overall, the diversified system reduced the total installed capacity by 19.35 MW in 2029 to 131.23 MW in 2048. The decline in the total installed capacity of the system is attributed to coal and gas, respectively, including nuclear technology. Total installed capacity decreased by 0.86% due to coal power at the end of 2048. Coal power was reduced by 152.47 MW in 2026 to 2,362.51 MW in 2048. Despite the marginal increase in gas installed capacity from 2026 to 2029, it also declined marginally from 231.76 MW in 2030 to 85 MW in 2035.

All other technologies neither increased nor decreased except the new installed capacity of nuclear technology, which ranges from 329.02 MW in 2029 to 2,231.26 MW at the end of 2048. The reduction in installed coal and gas capacity is largely due to the new capacity for nuclear power due to diversified simulations to include all planned technologies, while ensuring a clean energy transition agenda.

3.2.2. Generation capacity

The deviation in electricity generation capacity resulting from a diversified energy system is presented in Figure 7. In general, the diversified scenario includes a range of generation options that include gas, hydro, renewable, nuclear, coal, and some liquid fuels. The new generation capacity of nuclear technology ranged from 296.12 MWyr in 2029 to 1,975.4 MWyr at the end of 2048. The generation capacity for coal power declined significantly, ranging from 127.96 MWyr in 2026 to 1,975.41 MWyr in 2048. The decline in coal generation capacity from 2037 to 2048 is the same as the new generation capacity for nuclear technology.

Particularly, it was observed that the generation from coal technology has reduced, thereby, increasing that from nuclear technology. Hence, at the expense of coal, nuclear was installed with almost the same capacity, leading to no difference in the generation system from 2037 to 2048. Gas and hydro technologies declined marginally and added some generation capacity during the model period 2020 to 2048. The study's inclusion of nuclear with the earlier generation mix partly agrees with the competitive generation mix for the study in Saudi Arabia (Esmail & Cheong, 2021). Moreover, Herath and Jung (2021) revealed that the evolution of the generation mix from fossil fuels such as coal is important to transition to a low-carbon economy. Furthermore, the study by Mwanza and Ulgen (2020) added that a well-developed energy mix will improve the socio-economic and environmental conditions of nations. Hence, for Ghana, despite the inclusion of

Figure 6. Installed electricity capacity (MW).

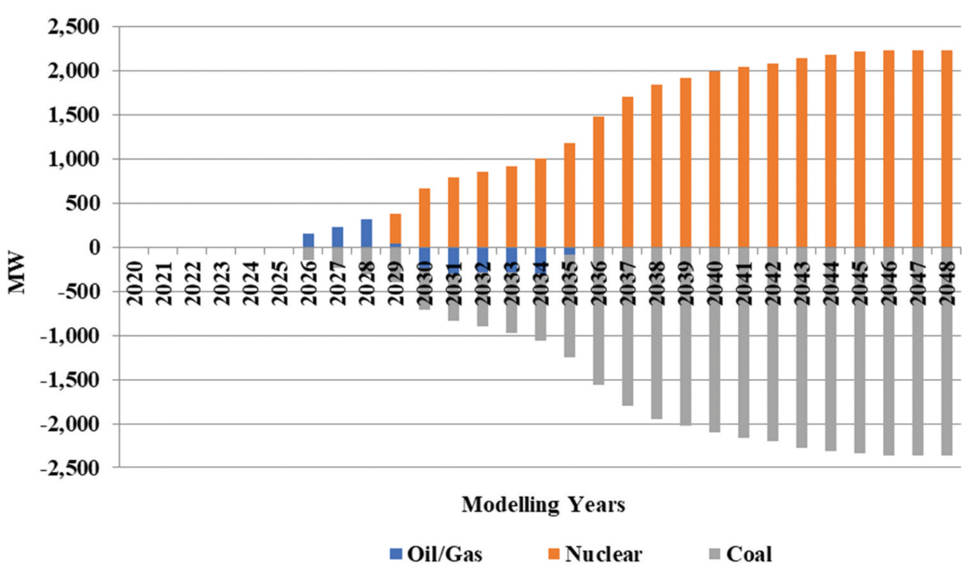
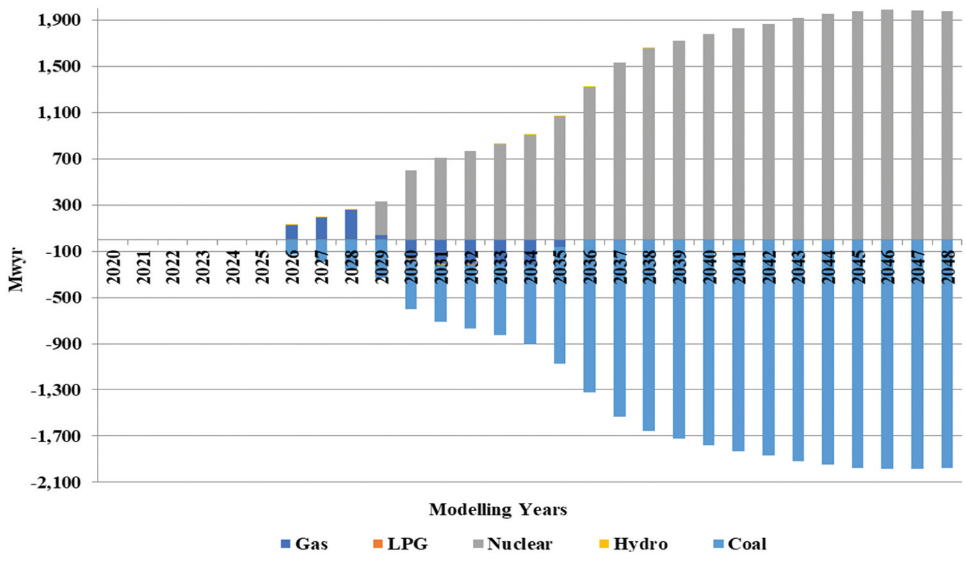


Figure 7. Electricity generation (MWyr).

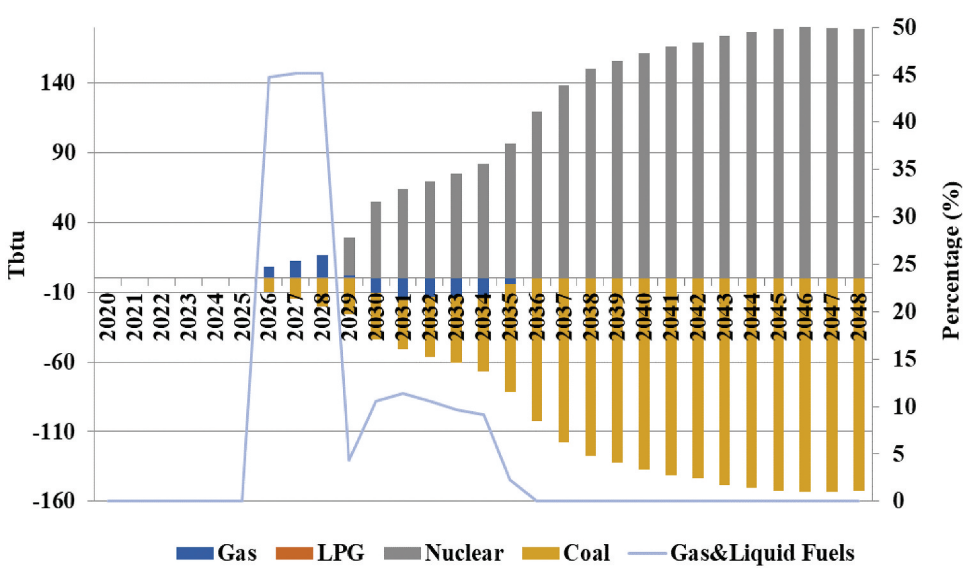


nuclear in the projections of the existing technologies, more is required to intensify a well-diversified commitment. As such, effective implementation of Ghana's energy policy to achieve the sustainability needed is key to national development.

3.2.3. Fuel consumption

As represented in Figure 8, the diversified fuel consumption included nuclear technology, making a difference in the scenario. Fuel consumption in 2048 increased by 26.67 TBtu, representing 6.59%, despite the decrease in installed capacity and no difference in generation capacity. The system increased the gas fuel consumption from 2026 to 2029 and reduced it from 2030 to 2035. Coal consumption was also reduced by 9.86 TBtu in 2026 to 152.27 TBtu in 2048. The new fuel consumption for nuclear ranged from 26.82 TBtu in 2029 to 178.94 TBtu in 2048. The diversified nature of the system further caused gas and liquid fuels, in general, to decline from 44.78% in 2026 to 2.26% at the end of 2035.

Figure 8. Fuel consumption for electricity generation (TBtu).



Overall, the entire system for the diversified scenario increased fuel consumption marginally highly attributed to the new capacity of nuclear technology. A scenario result that supports the country's energy policy includes nuclear and clean coal technologies as key baseload options to augment existing hydropower in a cost-effective and environmentally friendly manner.

3.2.4. Dispatch and generation cost

As a result of a diversified electricity generation system, the associated electricity dispatch and generation cost on average is represented in Figure 9. The system records a reduction in the dispatch cost ranging from 9.32 million dollars in 2026 to 174.57 million dollars at the end of 2048. The average dispatch cost will be 74 million dollars. Overall, the average generation cost declined by 0.35 \$/MWh in 2026 to 2.73 \$/MWh in 2048, representing 32.30% in 2048.

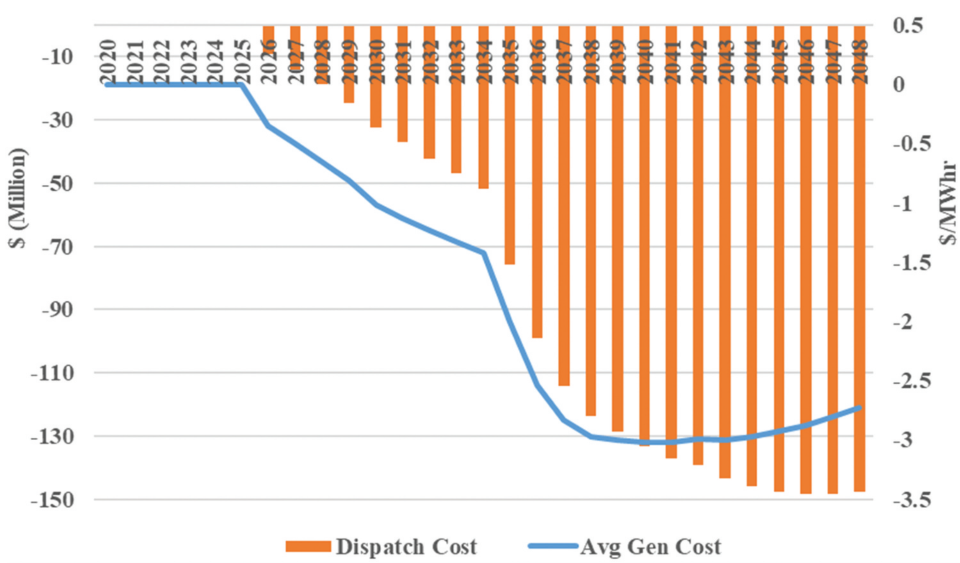
Therefore, a well-diversified and optimized electricity generation system will lead to a cost-effective generation mix as confirmed by Herath and Jung (2021) for Sri Lanka and Mwanza and Ulgen (2020). Ultimately, lower dispatch and generation costs can invariably lead to a low level of tariffs for final electricity consumers. Therefore, to achieve the ambition of Ghana's Energy Policy to attain long-term cost-effective power generation (Ministry of Energy Ghana, 2019).

3.2.5. Generation Emission Factor

Figure 10 represents the margin of CO_2 emissions resulting from the diversified nature of the generation system. In general, total generation emissions decreased by 0.036 kgCO_2/kWh in 2026 to 0.28 kgCO_2/kWh at the end of 2048, representing 55.27% in 2048. The reduction in CO_2 emissions is attributed to the inclusion of nuclear technology in the energy mix, with 603 MWyr in 2030 to 1,975 MWyr in 2048. The decrease in CO_2 emissions is attributed to the decrease in the capacities of the gas, LPG and coal technologies. As stated above, the reduction in coal capacity is the same as the new addition of nuclear technology capacity from 2037 to 2058. For this reason, the current study is important to influence policy direction since coal contributes nearly 40% of the world's CO_2 emissions from fossil fuels (Kaygusuz, 2009). Besides, the current study is confirmed by the work of Nyasapoh and Debrah (2020) that nuclear power is a cost-effective and low-carbon energy source for Ghana's climate change mitigation.

Thus, the reduction in energy sector emissions is affirmed by Bilgen and Sarıkaya (2018) to ensure sustainable economic development and a carbon-free economy. Therefore, a country's

Figure 9. Dispatch and Average Electricity Generation Cost.



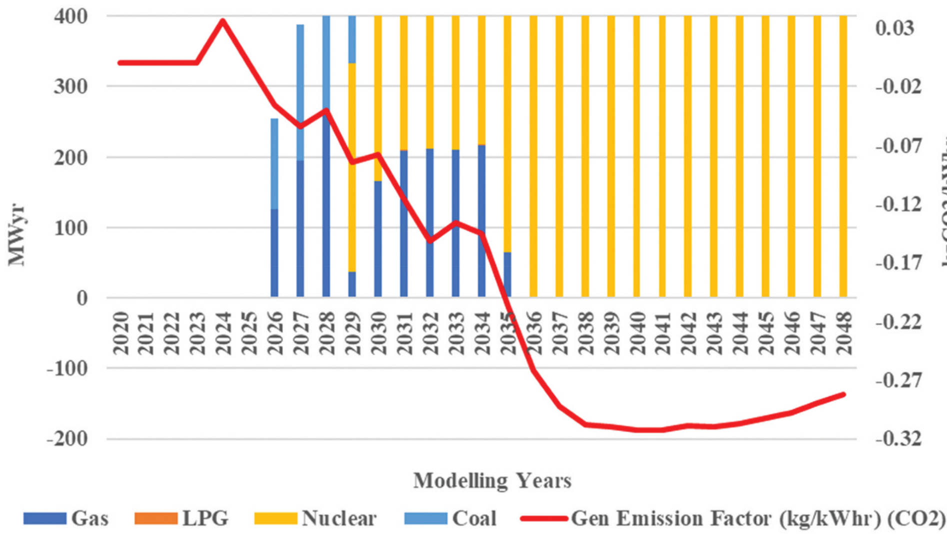


Figure 10. Generation emission factor.

electricity production must integrate environmental and socioeconomic impacts (Sareen & Nordholm, 2021). Consequently, an energy mix with low-carbon sources such as nuclear and renewables in the system is considered a key contributor to the long-term reductions in CO_2 emissions, as confirmed in the case of Saudi Arabia (Esmail & Cheong, 2021). Moreover, such reductions when successfully implemented will ensure a just energy transition as indicated by García-García et al. (2020).

3.3. Accelerated Economic Growth (AEG) electricity generation analysis

Once an economy develops, a key factor that influences the economy's growth is, no doubt, electricity. The AEG simulation analysis is made to ascertain the behaviour of Ghana's energy system in fast-growing energy demand as a result of accelerated economic growth (AEG). Like the diversified electricity analysis, the AEG analysis also reports the margin or deviations of the electricity generation output relative to the BaU.

3.3.1. Installed capacity

The representation in Figure 11 is the total installed electricity capacity for the AEG simulation results. The nature of AEG's expansionary electricity consumption also led to an increase in total installed capacity from 66.31 MW in 2020 to 13,557.65 MW at the end of 2048. The total installed capacity requires the additional capacities of oil/gas, hydro, coal, MSW, and solar technologies. The installed capacity increased by 46.91% at the end of 2048, mainly attributed to 24.91%, 13.70%, and 8.30% for coal, gas, and solar technologies, respectively. The main installed additional capacities include oil/gas ranging from 16.39 MW in 2020 to 3,958.46 MW in 2048, while coal ranged from 409.54 MW in 2023 to 6,883.59 MW in 2048. The additional solar capacity was the same from 2022 to 2045 with 2,400 MW and later in 2047 and 2048. Hydropower also had the same installed capacity of 0.77 MW from 2026 to 2048, and MSW installed 49.92 MW from 2020 to 2022. While the wind did not record any additional installed capacity, nuclear technology was not installed due to the high fixed overnight cost of 5,000 $/MW at a discount rate of 12%.

The installed capacity of the AEG can be considered to be not well diversified and has low penetration of renewables or low-carbon technologies. Despite the high electricity demand of the AEG simulation, the scenario did not install nuclear despite the technology's advantage to guarantee greater security of supply and non-emission of greenhouse gases (GHG) as dabbed in the energy policy (Ministry of Energy Ghana, 2019). This brings to the fore the assertion made by Bilgen and Sarıkaya (2018), that maintaining non-renewable energy resources for future generations as the main purpose of sustainability is a matter of concern. For this reason, Ghana's Energy Policy

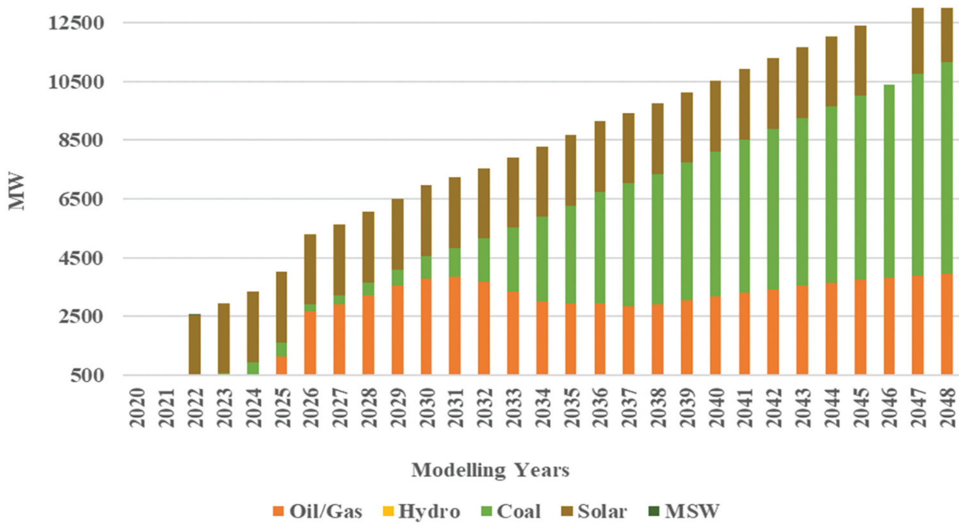


Figure 11. Installed electricity capacity (MW).

ambition to increase the capacity of low carbon energy sources for sustainable power supply to drive accelerated economic development is flawed with more inclusion of fossil fuel options, such as coal.

3.3.2. Generation capacity

As a result of the improvement in economic growth that leads to an increase in electricity supply to satisfy the growing demand, the generation capacity is represented in Figure 12. The total capacity margin increased by 408.09 MWyr in 2020 to 5,049.59 MWyr in 2048, representing 45.15% in 2048. Overall, the technologies that contribute to the generation capacity include gas with major additions from 2020 to 2035 and coal with a significant contribution of 319.24 MWyr in 2023 to 4,633.47 MWyr in 2048. Solar made the same generation capacity of 396.75 MWyr from 2022 to 2048. The increased generation capacity in 2048 is mainly due to 41.43% and 3.55% for coal and solar technologies, respectively.

The electricity generation from coal took advantage of the low average cost to supply in abundance for the high electricity demand capacity. However, Ghana's energy policy is cautious of the increased greenhouse gas (GHG) emissions concerns of coal power that pose challenges to

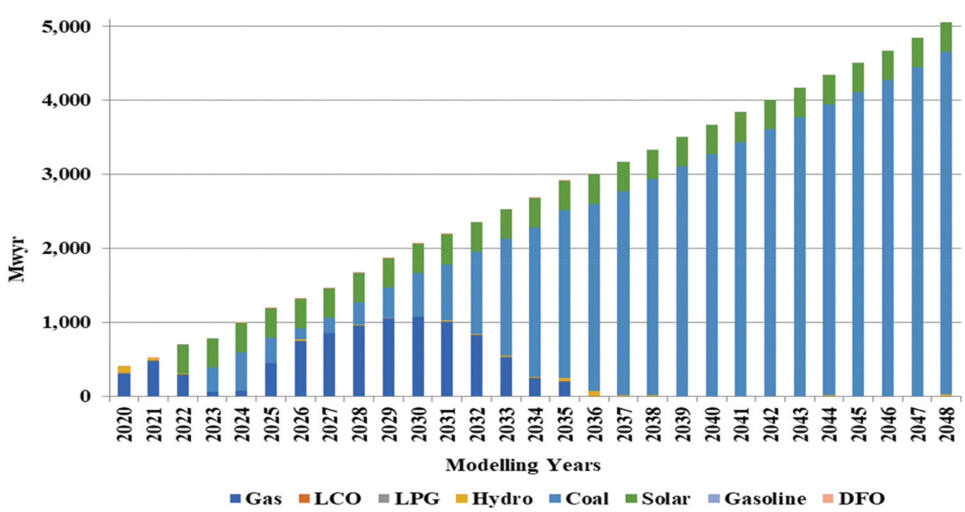


Figure 12. Electricity generation (MWyr).

climate change (Ministry of Energy Ghana, 2019). For this reason, the energy policy considers clean coal in addition to higher penetration of renewables and nuclear power.

3.3.3. Fuel consumption

The fuel consumption of the AEG is shown in Figure 13. The total fuel consumption margin increased from 21.60 TBtu in 2020 to 357.15 TBtu at the end of 2048, representing 48%, mainly attributed to coal in 2048. In general, the fuel consumption components included gas, LCO, HFO, LPG, coal, gasoline, and DFO. Gas and liquid fuels declined from 100% in 2023 to 0.09% in 2041 due to the increased coal consumption in the generation mix.

3.3.4. Dispatch and generation cost

The dispatch margin and the average electricity generation costs for the AEG are represented in Figure 14. The margin of increase in the average generation cost in 2048 is 1.55 $/MWh, representing 12.21%. In general, the high growth in the economy caused the dispatch cost to increase by 34.87 million dollars in 2020 to 642.91 million dollars at the end of 2048, with the dispatch cost of 296.69 million dollars.

Figure 13. Fuel consumption for electricity generation (TBtu).

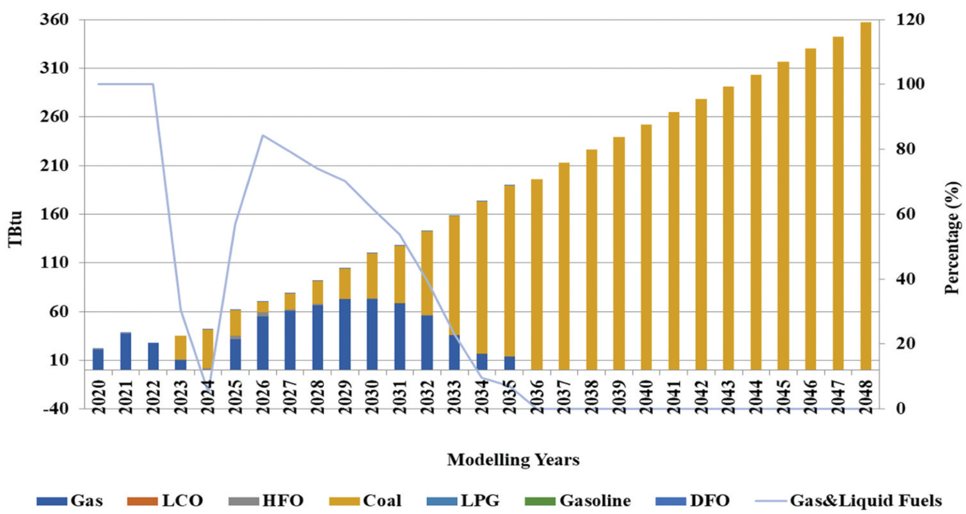


Figure 14. Dispatch and average electricity generation cost.

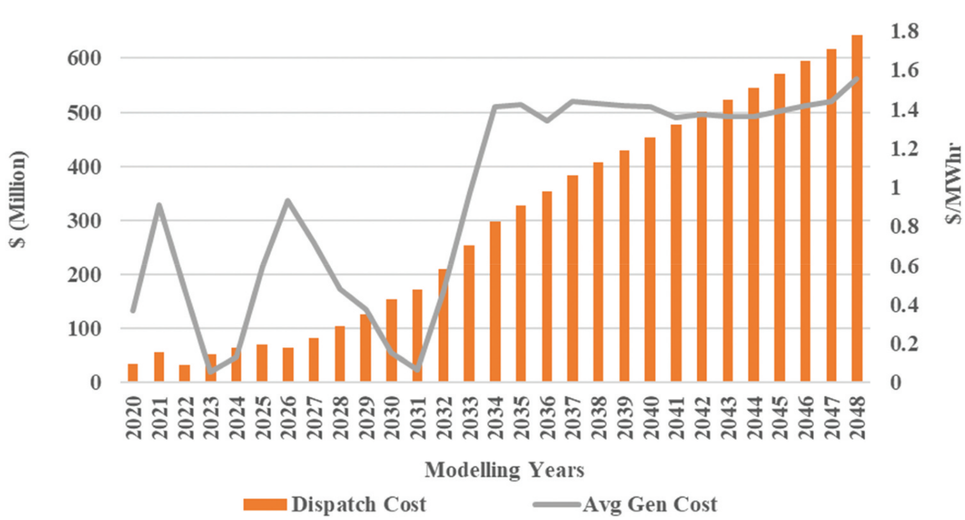
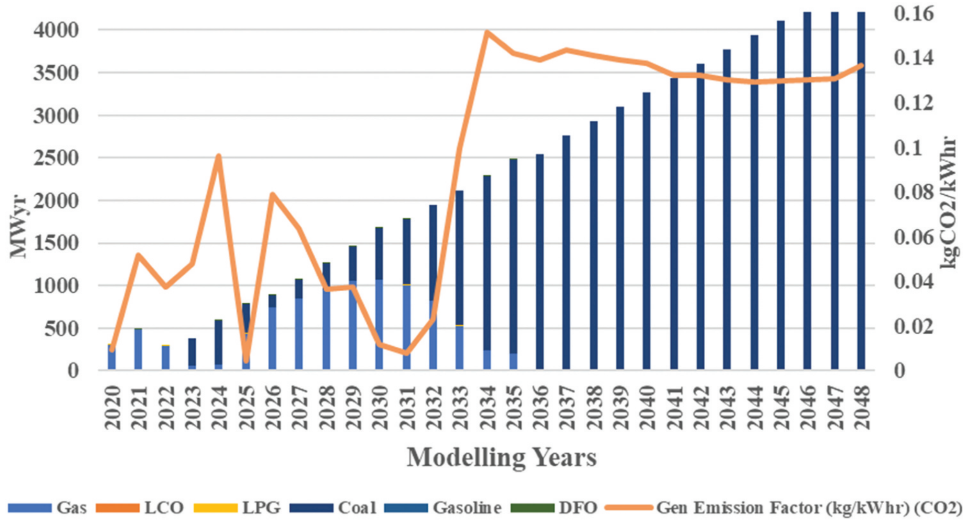


Figure 15. Generation emission factor.



The corresponding increase in the margin of the average generation cost of electricity ranges from 0.37 $/MWh in 2020 to 1.55 $/MWh in 2048. However, the system recorded a slower increase in the years 2023, 2024, and 2031. For an effective and robust cost of the generation system, there is a need for a well-diversified optimized energy mix in a low-carbon economy despite an increase in electricity demand. Such an attempt can lead to low tariffs to fulfil the Energy Policy's long-term ambition to attain cost-effective power generation (Ministry of Energy Ghana, 2019).

3.3.5. Generation emission factor

Figure 15 represents the margin of CO_2 emissions of the system for the AEG scenario. The margin of generation emissions increased from 0.009 kgCO_2/kWh in 2020 to 0.13 kgCO_2/kWh at the end of 2048, representing 21.10% in 2048. While gas technology contributes to the difference in CO_2 emissions from 2020 to 2035, coal contributed significantly to the system's emissions with the capacity of 4,633.47 MWyr in 2048. Therefore, the outcome of the study can impede the objective of sustainable electricity generation, since the environment and social lives can be damaged at the expense of electricity generation to develop Ghana's economy (Bilgen & Sarıkaya, 2018). Therefore, adopting energy security measures without environmental implications (Krishnan, 2016) will continue to have an increasing long-term equilibrium relationship between emissions and energy production (Asumadu-Sarkodie & Owusu, 2016).

The indication is that coal power has proven to contribute immensely as a baseload electricity source for cheap supply. However, the energy policy is aware of emissions highly attributed to coal (Ministry of Energy Ghana, 2019), as proven in the AEG simulation assessment. The future electricity generation mix with high coal consumption will further hinder the energy transition agenda. Therefore, Awopone et al. (2017) indicated that alternative least cost generation options require suitable policies for clean power generation to play an important role in the mitigation of Ghana's CO2.

4. Policy implications

As dubbed by Bilgen and Sarıkaya (2018), the need for a sustainable future with electricity generation is a major challenge for humanity. Ghana's energy policy for the past decades has shown the role of electricity in fostering economic growth. The 2019 Energy Policy draft, in line with SDGs 7 and 13 aimed at ensuring access to affordable, clean, and sustainable energy. The energy policy tends to have a high penetration of renewables and baseload energy sources such as clean coal and nuclear technologies. Also, the 2020 Renewable Energy (Amendment) Bill added that all water-based energy systems are classified as renewables. Moreover, nuclear energy has been considered part of Ghana's clean energy alternatives (Ministry of Energy, 2020). Even though the 2019 Energy Policy draft, and all other national energy policies do not depict the proportions of various sources, the 2019 Energy Policy draft somehow mentioned all the energy sources under consideration in this study.

Therefore, Ghana's energy balance not in the right proportions of energy sources in the generation mix may undermine most of the successes achieved over decades. Thus, the assessment of this study's results revealed that a balance of fuel is needed for each scenario to influence effective policy direction in the long term. On average, the percentage of each fuel source for a diversified energy mix is projected as 42.21% for gas, 0.52% for liquid fuels, 23.7% for nuclear, 14.69% for hydro, 15.28% for coal, 1.60% for wind and 2.0% for solar. Finally, the generation mix of each fuel option for the AEG in terms of percentage is estimated to be 30.51% for gas, 0.36% for liquid fuels, 9.01% for hydro, 52.51% for coal, 0.98% for wind, and 6.63% for solar.

Therefore, Ghana's short-to-medium and long-term energy policies must determine the acceptable percentages based on the outcome of cost optimization as has been carried out in this study. Furthermore, despite the definition of coal in the 2019 Energy Policy as clean coal, investment in coal is dwindling. This situation of coal may lead to Ghana experiencing the challenge of finding the right investment in coal as the Nationally Determined Contributions climate commitments come into the implementation phase.

Additionally, the higher penetration of coal technology in the BaU and AEG scenarios saw a rising CO_2 emission that impedes the ambition of Ghana's climate change commitment to either limit or alleviates GHG emissions that cause climate challenges. The inclusion of more oil and gas coupled with high cost and capacity charges could lead to a relatively high cost of electricity generation, which will in effect cause a hike in electricity tariffs.

Overall, the continued electricity generation on the BaU scenario path would go against the intervention sorted by the Energy Policy to encourage low-carbon energy options in a diversified, sustainable, cost-effective, and environmentally friendly manner. Hence, it is essential to re-look at the energy policy for an alternative that can serve as the baseload just like coal with an even higher capacity factor.

4.1. Long-term energy transformation agender for Ghana

The sustainable electricity generation plan for Ghana hinges on a robust national energy infrastructure plan that will stimulate the needed economic growth. For that matter, all national energy policy agendas need to be coherent with Ghana's long-term energy transformation agenda, championed by the National Development Planning Commission (NDPC) (NDPC, 2016). Following the long-term development agenda for Ghana, the electricity generation per capita is expected to increase from the current 534 kWh per annum (Energy Commission Ghana, 2021) to about 5,000 kWh per annum by 2030 (Ministry of Energy Ghana, 2019) and further to 5,850 kWh in 2047 (NDPC, 2016). Figure 16 illustrates the long-term energy sector development plan for Ghana.

5. Conclusions

Faced with the dual objective of generating electricity in a cost-effective and low-carbon environment, the study carried out a simulation analysis to assess energy resources for sustainable electricity generation as captured in Ghana's Energy Policy. The assessment and analysis were made on the cost and CO_2 emissions associated with electricity generation for three major scenarios: business as usual (BaU), diversified, and accelerated economic growth (AEG). The electricity generation from installed technologies/power plants for the BaU and AEG scenarios included gas, hydro, solar, wind, MSW, coal and liquid fuels. Furthermore, the diversified scenario had nuclear power technology as part of the existing technologies for the BaU and AEG scenarios. Invariably, the long-term analysis of electricity generation emphasized the need for sustainable electricity generation on the backdrop of the triple bottom line of economic growth, improvement of social life, and lowering emissions to save the planet.

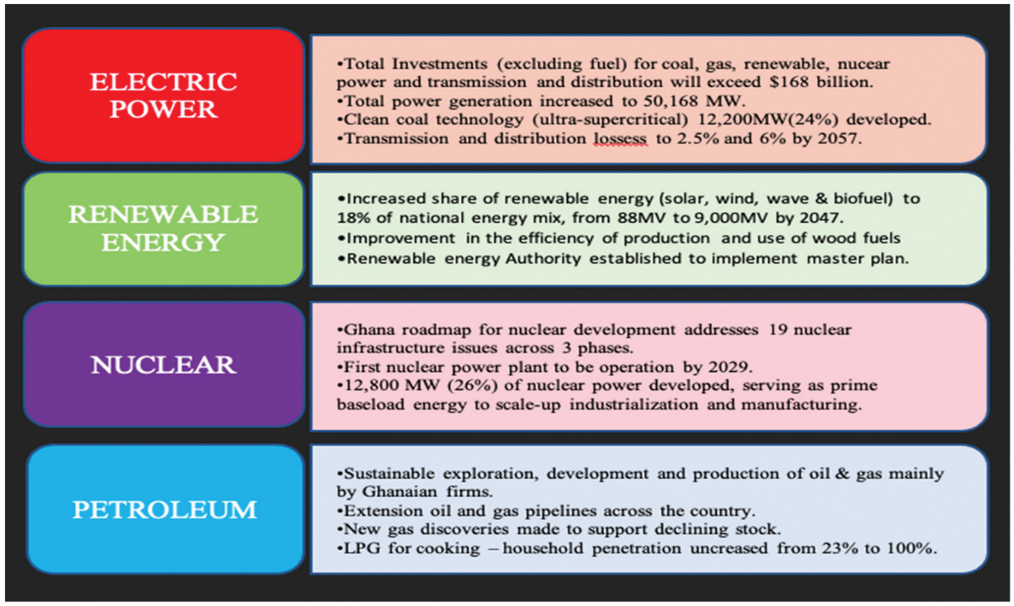


Figure 16. Long-term energy infrastructure (2018–2047) plan for Ghana (NDPC, 2016).

The BaU assessment indicated that Ghana would require 70.7% of coal fuel consumption against 29.3% of gas consumption for electricity generation by 2048. Comparing the BaU to diversified and AEG scenarios further revealed that the margin of electricity generation cost on the average for the diversified and AEG scenarios in 2048 decreased by 2.73 $/MWh (32.30%) and increased by 1.55 $/MWh (12.21%), respectively. Comparatively, the CO_2 emission at the end of the period 2048 for the BaU was determined as 0.51 kgCO_2/kWh and the margin of decrease for the diversified was found to be 0.28 kgCO_2/kWh (55.27%), and the margin of increase for the AEG was 0.13 kgCO_2/kWh (21.10%). It was further revealed that even with a high electricity demand such as the AEG scenario, a business-as-usual electricity generation is not well diversified and emits a high amount of CO_2 emissions and low penetration of solar and wind sources.

Therefore, it can be concluded that a well-diversified electricity generation system for Ghana can lead to a cost-effective energy mix. Ultimately, a more optimal electricity generation system with low carbon energy options will not only lead to a green energy transition but will also cause a decrease in both dispatch and average generation costs. Reduced expenses can invariably lead to low long-term tariffs for the final consumer of electricity. Furthermore, the proportion of CO_2 emitted by the energy sector will be best short-lived in the long term with greater penetration of renewable and other low-carbon energy sources, such as hydro and nuclear technologies. Therefore, the successful implementation of energy policy requires an informed commitment to a long-term sustainable energy mix.

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