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Research Article

Estimation of CO_2 Emissions of Fossil-Fueled Power Plants in Ghana: Message Analytical Model

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The pursuit of middle-income economic status by Ghana comes with an associated increase in electricity and energy demand. Meanwhile, an increase in either electricity or energy consumption is likely to result in greenhouse gas (GHG) emissions as a result of increasing reliance on fossil fuel consumption. Presently, there is evidence of the impact of climate change on various aspects of Ghana's socio-economic structures such as energy production, agriculture, and forestry. Therefore, it is imperative to develop and implement a long-term low-carbon sustainable energy supply strategy that will support the electricity demand of the major economic ambitions envisaged. This study applied a quantitative modelling and simulation methodology using the Model for Energy Supply Strategy and their General Environmental Impacts (MESSAGE) analytical tool to analyse the electricity generation system and the impact of fuel options on the environment. It was found that the inclusion of low-carbon emission energy conversion technologies such as renewables and nuclear energy is critical to curtailing carbon dioxide (CO_2) emissions in Ghana's energy sector. Therefore, the incorporation of climate-friendly energy sources into the electricity sector is necessary to achieve sustainable, resilient, and clean electricity generation. Ghana's fulfilment of its international commitment to climate change depends on reducing its dependence on fossil fuels for electricity generation, thus, exploring the inclusion of zero-emitting sources into the country's energy mix.

1. Introduction

As a result of severe climate change issues and sustainable energy solutions, the world's energy solutions have been expressed in several ways ranging from mitigation to adaptation [1]. Therefore, the indication is that current energy policies are likely not to achieve the so-called universal access to modern energy by 2030 [2]. Hence, sustainable energy solutions resulting from climate change impact concerns require the consented effort of well-diversified policy ambitions and commitment [2]. Almost half of the global contribution to CO_2 emissions is attributed to electricity generation and heat production [3]. It, therefore, implies that fossil fuel sources for electricity generation still dominate the landscape causing negative impacts on the environment [4]. That notwithstanding, electricity remains a dominant force in driving Ghana's socio-economic development.

Based on Ouedraogo [5], several energy sector assessments have been made to influence policy decision-making for sustainable energy solutions. Among the key reasons for developing energy system models for assessment are the volatility of oil prices and the subject of climate change. Hence, modelling the energy sector for optimal solutions and the implementation of policy issues is essential to avoid future electricity generation challenges [6]. Esmail and Cheong [7] applied the MESSAGE tool for the optimal long-term generation strategy for Saudi Arabia. The study revealed that an electricity generation mix with the inclusion of advanced traditional thermal plants, nuclear, and renewable technologies(mainly solar and wind), will serve as a sustainable and competitive generation mix for Saudi Arabia. Ouedraogo [2] applied the "Long-range Energy Alternative Planning (LEAP) model" for a system-based approach to Africa's energy system. The study revealed that high emissions of greenhouse gases and supply shortages will be prevalent in the African energy sector by 2040 [5]. Seck and Toba [8] used a tree-like exploration methodology to assess future grid developmental strategies in West Africa. The methodology 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 [8]. The review by Asumadu-Sarkodie and Owusu [9] sorts to create awareness of Ghana's energy sector strategic planning and energy policies to serve as an informative tool for decision-making on efficient development and utilization of energy resources. Additionally, the study by Nyasapoh [6] explored a long-term energy supply strategy to ensure future electricity demand is met sustainably while maintaining a low-carbon environment, using the Energy Supply Strategy Model and their General Environmental Impacts (MESSAGE) optimization model. The study concluded that while the energy sector requires research, the electricity supply in Ghana should be optimized [6]. In addition, by simulating conventional and nonconventional energy technologies, Awopone et al. [10] applied an open source energy modelling system (OSeMOSYS) for long-term energy planning. The study concluded that low-carbon energy options for electricity generation play an important role in the mitigation of carbon dioxide (CO_2) in Ghana [10]. Also, Agyekum [11] adopted a SWOT analytical approach to assess the strengths, weaknesses, opportunities, and threats of Ghana's renewable energy sector and revealed that the exploitation of renewable energy sources in Ghana can enhance energy sector emission reduction. In addition, the study by Abokyi et al. [12] confirms that the adoption of low-carbon energy sources for electricity generation in Ghana will combat global warming challenges. As part of energy planning studies, the work of Nyasapoh and Debrah [13] determined the role of nuclear power as a cost-effective and low-carbon energy source for the mitigation of Ghana's climate change. Furthermore, [7] stated the various advantages and also used the MESSAGE model for a proposed approach that seems to provide more flexible strategic options for countries entering nuclear energy.

Ghana is currently a low-middle-income economy with a gross domestic product (GDP) of $72,340 million, with the ambition to achieve middle-income economic status by 2030 [14]. The country's objective to increase electricity consumption per capita is geared towards increasing electricity consumption from a current average of 534 kWh per capita per year [14] to an average of 5000 kWh per capita per year by 2030 [15]. Among many other African countries, Ghana is rich in the energy resources needed for electricity generation [6, 16, 17]. Ghana's current electricity access rate stands at about 85.33% [14], placing the country as one of the best in the sub-Saharan African region, thereby a good impact on reducing energy poverty [18]. However, Diawuo et al. [18] revealed that there exists a bottleneck in Ghana's electricity sector on the premise of environmental sustainability. As such, the study by Nyasapoh [6] stated that meeting the final electricity demand without concerns about environmental impact is a cheaper option. Data from the Ghana Energy Commission on electricity generation indicate that the country's total installed electricity capacity in 2020 is 5,288 MW [14]. Despite the alarming challenges of emissions, the country's current installed power generation capacity is dominated by thermals that consume fossil fuel representing 69.00%, followed by hydropower with 29.88% and 1.12% from renewables, mainly solar [14]. Although the overreliance on fossil fuels for conventional power generation is widespread, the electricity supply in Ghana has not been reliable in the past three decades. That notwithstanding, Ghana's 2019 National Inventory Report (NIR), also submitted to the UNFCCC, revealed that the effect of climate change is seen in various facets of the Ghanaian economy with a high reliance on energy production, agriculture, and forestry sectors. [19] Thus,out of the total greenhouse gas (GHG) emissions of 42.15 $MtCO_2e$, the energy sector ranks second with approximately 35.63% [20]. Out of the total energy sector contribution, the country's electricity generation alone provides 19% of the GHG emissions [21].

Before signing the Paris Agreement in 2016, the country submitted some Nationally Determined Contributions (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. The NDC's constitute several mitigation strategies against climate change with an overall objective of unconditionally reducing greenhouse gas emissions [22]. Thus, the country's goal of emission reduction is to unconditionally reduce its GHG emissions by 15% compared to a business as usual (BAU) scenario emission of 73.95 $MtCO_2e$ by 2030. Besides, a 30% emission reduction is attainable on the condition that external support is made available to Ghana to cover the full cost of implementing the mitigation action [19]. The country's emission reduction strategies are not expected to inhibit the country's long-standing agenda of becoming a "full-fledged upper-middle-income economy" [19].

Ghana recognizes the challenge of achieving adequate electricity supply, ensuring reliability, affordability, and expanding the electricity infrastructure in a low carbon environment [15, 23, 24]. Therefore, it is important to develop an optimal mix of electricity generation that takes advantage of the maximum potential of less emitting energy sources for electricity generation [15]. In addition, energy system models aid the policy decision-making process by providing efficient energy supply strategies for electricity generation [25]. Hence, the combination of power options in a flexible manner will optimize Ghana's energy mix for long-term planning [7]. On that premise, the Energy Commission of Ghana [26] developed the Strategic National Energy Plan (SNEP I) to create a sound energy market by formulating a comprehensive plan that will identify the optimal path for Ghana's energy development.

This study, therefore, has adopted a quantitative modelling methodology to analyse the electricity generation system and the impact of fossil fuel options using the MESSAGE analytical tool. The study has also evaluated the potential role of other energy options on the environment. Therefore, the analysis of the study of fuel emissions will be essential for influencing policy on CO_2 emissions mitigation measures in the power sector. The study will also be key to the contribution of literature in the landscape of energy sector emission analysis.

2. Electricity Demand Projections

The electricity system consists of demand and supply scenarios. Every supply situation requires a corresponding demand to satisfy. To better estimate the CO_2 emissions of fossil fuel power plants in Ghana's electricity supply, the study used the demand projections of the Ghana Energy Commission, the state institution responsible for energy planning.

The Energy Commission of Ghana used the Long-range Energy Alternatives Planning (LEAP) model to determine the electricity demand projections based on the average and current performance of the Ghanaian economy [27]. The projection data of the electricity demand served as the exogenous input variable for the MESSAGE model of the study. Figure 1 represents the business as usual (BaU) electricity demand projections for Ghana.

Thus, the final electricity demand required for Ghana is projected to increase from 18,542 GWh (1,594 ktoe) in 2020 at an average annual rate of 5.1% to 30,570 GWh (2,629 ktoe) in 2030 [27]. To add up to the total electricity demand after 2030 for the BaU scenario projected by the Energy Commission, the study extrapolated the data to 2048 to suit the long-term projection of the study, which is within the long-term development plan (that is, 2018 to 2057) of Ghana [28].

3. Methodology

This article used the MESSAGE analytical model, a computational optimization model, to evaluate the feasibility of energy supply strategies and the possibility for Ghana's electricity sector to contribute to national emission reduction targets. The study applied the MESSAGE model to the Ghanaian electricity supply system consisting of existing and yet to be installed electricity supply infrastructure.

The "Model for Energy Supply Strategy and their General Environmental Impacts (MESSAGE)" is a dynamic linear programming (DLP) model that minimizes the total discounted energy supply costs over a given time horizon [29–31]. The model's primary function is to balance the demand for secondary or final energy and the supply of primary energy resources via diverse technologies. The main characteristics of the model are consideration of the load regions for the demand for electricity, the disaggregation of resources into cost categories, and the environmental impact of energy [29]. The specific point of application of the MESSAGE model is to formulate and evaluate alternative energy supply strategies constrained by user-defined scenarios [30].

The MESSAGE model, which is readily available to the authors, provides potential solutions to a dynamic linear program by optimizing an objective function defined within a feasible region [29, 30]. The MESSAGE model is relevant to this study because of its extensive application in studying the consequences of alternative lines of action and alternative sets of constraints on energy supply decisions. MESSAGE is a widely used model as one of the best optimization tools, and, for many national energy optimization analyses [32, 33]. Additionally, IIASA (2020) revealed that scenarios developed with the MESSAGE model have been used in the assessments and special reports of the Intergovernmental Panel on Climate Change (IPCC) and most recently the Global Energy Assessment (GEA) [34]. Besides, the MESSAGE model was used to generate one of the four Representative Concentration Pathways (RCPs) currently used to estimate future climate change in the context of the IPCC 5th Assessment Report [32]. Currently, the International Renewable Energy Agency (IRENA) and the International Atomic Energy Agency (IAEA) are serving as model partners for the development of the African Continental Power Systems Master Plan (CMP). In that regard, the IAEA's MESSAGE model will be used to support the CMP team in the development to ensure knowledge transfer and capacity building [35].

3.1. Case Study Parameters and Key Assumptions. The modelling period consisted of 30 years within the long-term development plan (2018-2057) envisaged by the National Development Planning Commission (NDPC) of Ghana.

Electricity supply scenarios modelled were based on the following:

(i) The Ghana Energy Commission projected the reference scenario, otherwise termed business as usual (BaU), in the electricity demand projections

(ii) The study period spans from 2018 as the base year to 2048, a 30-year study period with discussions from 2020 to 2048. The year 2018 was used as the base year because it has the most stable electricity system in Ghana. The study period of 30 years is in line with the 40-year long-term National Development Plan (2018-2057) of Ghana [36]

(iii) For the reference scenario, all potential power plants or new builds were modelled with no constraints or limits except the bounds on renewable energy sources, i.e., the maximum potentials of solar irradiation capacity of 6.0 kWh/m^2/day and wind speed at 6 m/s at 50 m above sea level

(iv) Compared to the BaU scenario, the study modelled the emission fuel effect scenario (EFES) of a 15% reduction in CO_2 emissions in line with Ghana's intended nationally determined contribution (INDC) [19]

(v) The energy system modelling was based on Ghana's GDP growth, electricity demand, technology cost

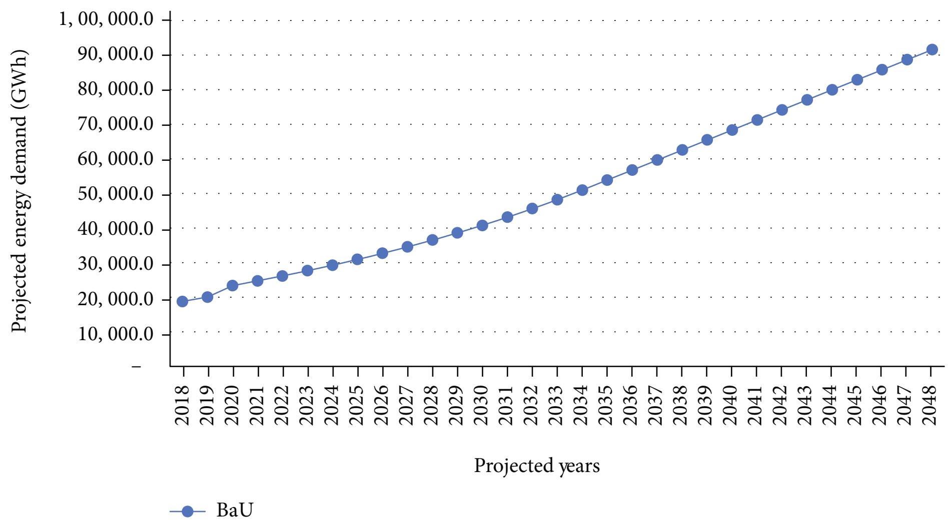

Figure 1: Projections of energy demand for the economy of Ghana, 2019.

overnight, gas resource availability, and unlimited imports.

(vi) A discount rate of 12%, used for the procurement of power plants in the country, was used with a 20% reserved margin on the system

3.2. Electricity Supply System and Reference Electricity System. The electricity supply system for Ghana is made up of resources linked to a primary energy level where the resources are converted to primary energy using electricity supply/conversion technologies (power plants). The primary level is linked to the secondary level, for the primary energy sources to be converted to secondary using the conversion technologies. The converted energy from the secondary level is then sent through a transmission and distribution system to get to the final electricity demand for end use. All resources, comprising of primary, and secondary fuels considered for electricity generation represented in the study included hydro, oil/liquid fuels (i.e., HFO, LPG, DFO, LCO, and gasoline), natural gas, solar, wind, municipal waste (MSW), coal, and nuclear.

A reference electrical system (RES) is a network flow of the energy system or energy carrier from one process to another, from resource to final consumer [16] [17]. The principle of the RES aided the simulation and modelling of the electricity supply system for Ghana by use of the MESSAGE analytical tool, thereby permitting the representation of the entire electricity supply network, including possible development paths.

3.3. Empirical Model. The MESSAGE model combines technologies and fuels to construct a network supposedly referred to as "energy chains," which makes it possible to map energy flows from the supply (resource extraction) to demand (energy services) [31]. The study applied the MESSAGE model to the Ghana electricity supply system that includes the existing and yet to be installed electricity supply infrastructure. The study model has the objective of minimizing the sum of discounted costs or the net present value of the overall electricity supply system [29, 30].

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

where T is the number of periods in the model; j and t are the technology and period, respectively; d_t^o and d_t^c are the discount factors applied for operating and capital costs, respectively; Δ_t is the length of the period t in years; X_{jt} is the fuel consumption of technology j in period t; Y_{jt} is the capacity variables for annual new installation of technologies; i_{jt} is the specific investment of technology j at period t; and O_{jt} is the 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 follows:

$$\begin{gathered} \sum \text{supply} \geq \text{Demand} \\ \sum_{j=1}^{J} \sum_{i=1}^{I} \eta_{i,j,t} \times x_{i,j,t} \geq D_{i,t}, \end{gathered} \quad (2)$$

where t is the period of study, η is the efficiency of the plant, x is the installed capacity, i is the modelling years, j is the conversion technology, and D is the electricity demand.

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

$$\sum \text{Production} - \sum \text{Consumption} \geq 0,$$
$$\sum_{j=1}^{J} \sum_{i=1}^{I} \eta_{i,j,t} \times x_{i,j,t} - \sum_{v=1}^{V} x_{v,i,t} \geq 0. \tag{3}$$

Furthermore, the installed capacities are described by the technology capacity equation presented as follows:

$$\eta_T \times x_T - \sum_{t=1}^{T-1} \pi_t \times y_t \leq \pi_T + Y_0, \tag{4}$$

where Y_0 is the historical capacity, y is the new installations, and π is the plant factor.

Accounting for environmental impact is given by employing as follows:

$$\text{Upper Limit} > \Sigma\,(\text{EF}i * \text{FUEL}i) > \text{Lower Limit}, \tag{5}$$

where FUELi is the fuel used by conversion technology i and EFi is the coefficients with which technology is entering a relation.

The EFi in (5) is defined as

$$\text{EF}i = \text{CEF} \times \frac{44}{12} \times \text{Oxydationfacor} \times 8.76 \times \frac{3.6}{1000}, \tag{6}$$

where CEF is the carbon emission factor. The values of various fuel CEF and their oxidation factors are obtained from the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Workbook.

The environmental constraints in this study were first analysed by accounting for the CO_2 emissions related to the generation technologies. The study then placed a cap of 15% reduction in CO_2 emissions by the electricity generation technologies in the system [31, 37]. The decision to place a 15% reduction in the CO_2 emissions cap is in line with Ghana's NDC unconditional emission reduction mitigation strategy [19]. The model supported the evaluation of environmental impacts in the development of the electricity supply system [31]. This process was to determine the impact of fuel options and the potential role of other energy sources in the mitigation efforts to combat climate change in Ghana.

4. Discussion of the Results

The results of the study are discussed according to the scenario developments. First, the base case scenario is discussed, followed by the emission reduction scenario to portray the effect of fossil fuel options on Ghana's electricity generation.

4.1. Reference Scenario. The business as usual (BaU) scenario serves as the reference case for the study's electricity system analysis. The base year for the study is 2018, with a total installed capacity of 4,396.67 MW; however, all discussions in this paper commenced from results in the year 2020 to 2048.

As represented in Figure 2, the modelldelectricity system will require 4,788.11 MW in 2020 and 15,344.56 MW at the end of the model year 2048. Among the seven (7) modelled technologies, all except nuclear and municipal waste (MSW) were not installed in the base case. The oil/gas installations dominated the electricity installed capacity system, followed by the installations of coal, hydro, solar, and wind technologies, respectively.

Among the renewable energy sources, solar technology has been somewhat encouraging in the last five years of the study. The inability of nuclear to make any stride in the system is largely attributed to the high relative overnight fixed cost of 5,000 \$/MW at a discount rate of 12%. The total installed capacity of renewables was largely attributed to the nongrid connection largely attributted to solar rather than wind or any other renewable energy source in the system.

The total generation capacity at the end of the 2018 base year was 1,566.0 MWyr. Following the installed capacity in the power system in Figure 2, the energy generation technologies/power plants were allowed to generate without limitations to satisfy the capacity for electricity demand. Figure 3 represents the total generation of electricity per type of fuel consumed during the study period 2020-2048. The entire demand curve of the system shows the trend of the electricity generated in the system to satisfy the required demand for 2020 to 2048. Thus, the system will require a generation capacity of 2,197.5 MWyr in 2020 to 6,173.2 MWyr in 2048. The generation system at the end of the study period 2048 requires the capacities of gas 1,746.3 MWyr, hydro 670.9 MWyr, coal 3,464.4 MWyr, and solar 291.5 MWyr. Liquid fuels made strides between 2020 and 2048 to generate electricity, while wind ended in 2034 with a generation capacity of 128.9 MWyr.

CO_2 emissions and generation emission factors have been assessed and are represented in Figure 4. Total CO_2 emissions will increase from 3,951.02 kilotons in 2020 to 27,615 kilotons in 2048. The CO_2 emissions will emit 13,880 kilotons on average on the entire system from 2020 to 2048. The corresponding generation emission factor will increase from 0.21 $kgCO_2$/kWhr in 2020 to 0.51 $kgCO_2$/kWhr in 2048 and emit an average of 0.35 $kgCO_2$/kWhr in the system from 2020 to 2048. The CO_2 emissions under the BaU scenario at the end of the study period 2048 are attributed to the total installed capacity of fossil fuels of 12,205.11 MW, made up of 7,388.5 MW and 4,816.61 MW for oil/gas and coal, respectively.

Although Ghana's 2019 energy policy draft [15] is aware of the relatively high greenhouse gas (GHG) emissions attributed to fossil fuels, the results of this study indicated that the electricity system in 2048 will require 28.3% and 56.1% of gas and coal generation technologies, respectively. Despite the assertion by [38] that there exists some hope of possible medium-effects of mitigation measures to slow the growth of Ghana's emissions. However, unplanned and cheaper fuel sources, such as coal for electricity generation, will hinder Ghana's CO_2 emission mitigation measures. Therefore, including low-carbon energy options for

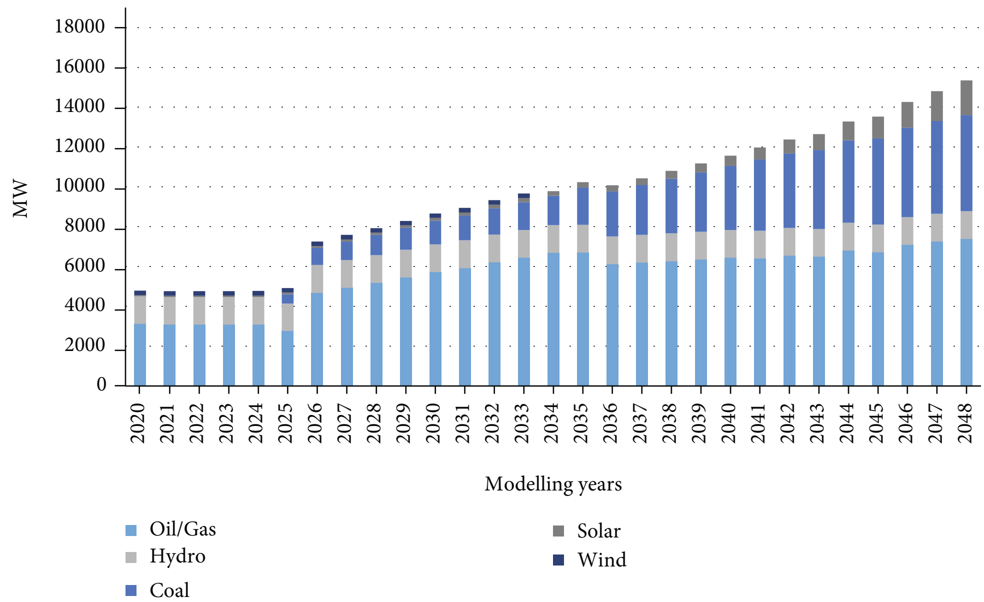

Figure 2: BaU total installed capacity of the electrical system (MW).

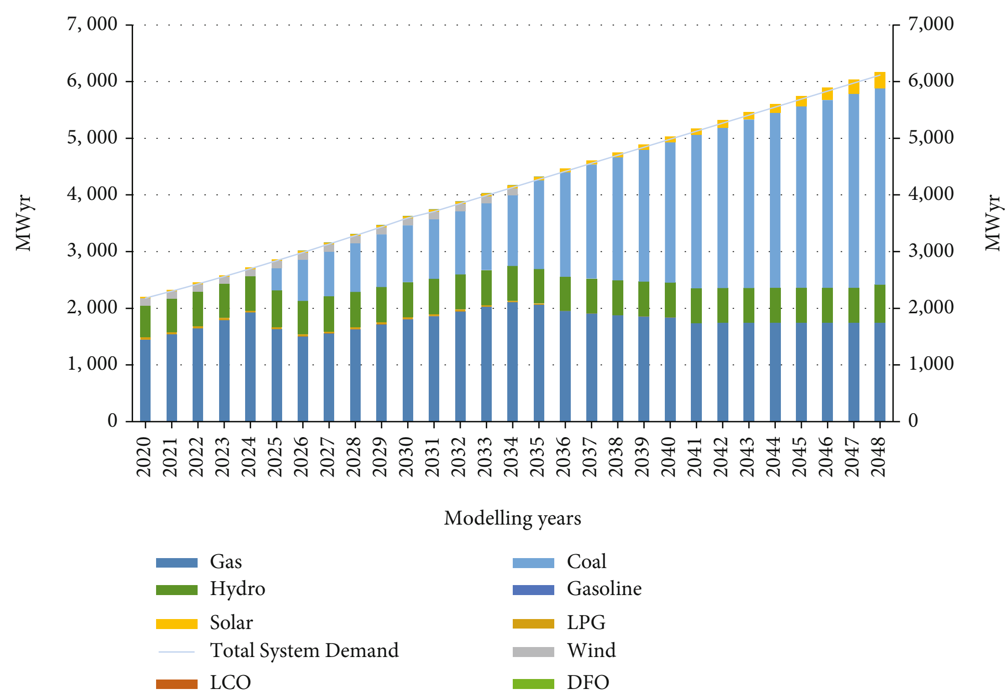

Figure 3: BaU electricity generation per fuel consumption (MWyr).

electricity generation is a good way to mitigate CO_2 emissions from the power sector in Ghana while saving the planet.

4.2. Emission Fuel Effect Scenario (EFES) by 15% Reduction. The scenario is termed the emission fuel effect scenario (EFES) since it estimates CO_2 emissions from fossil fuel power plants in Ghana. All parameters in the reference case or BaU scenario were kept constant for the EFES except a 15% CO_2 emissions constraint to limit the emissions associated with CO_2 emitting technologies/power plants.

Unlike the base case, EFES has increased the number of installed technologies/power plants by one, i.e., the inclusion of nuclear technology with 4,396.67 MW total installed capacity for the base year 2018. Figure 5 shows that the study period requires a total installed capacity of 4,788.11 MW in 2020 to 15,287.26 MW in 2048.

The results indicated that at the end of the study period 2048, the total installed capacity for EFES was

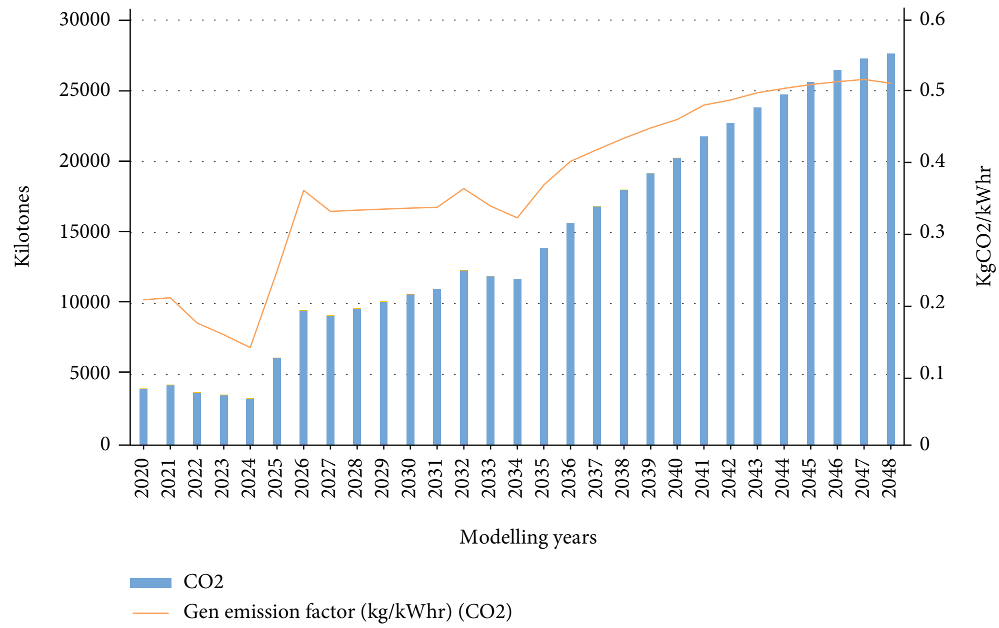

Figure 4: BaU CO_2 and generation emission factor.

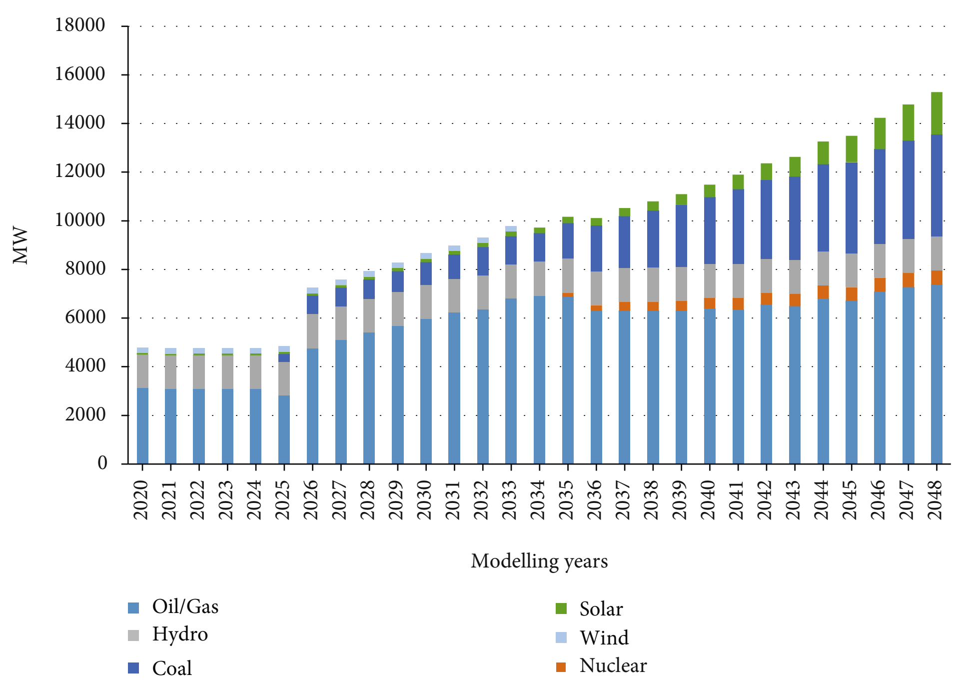

Figure 5: EFES total installed capacity on the electricity system (MW).

reduced by 0.37% (57.30 MW) compared to the BaU scenario of 15,344.56 MW. The reduction in installed capacity for the EFES in 2048 is mainly attributed to the increase in capacity factors due to the addition of new coal and nuclear plants.

According to the installed capacity of the power system in Figure 5, electricity generation was based on the EFES parameters with a total generation capacity for the base year of 1,566.0 MWyr. The generation capacity on the overall system represented in Figure 6 is similar to the generation capacity in Figure 3 for the BaU scenario. The generation capacity illustrated in Figure 6 requires a total installed capacity of 2,197.5 MWyr in 2020 to 6,173.2 MWyr in 2048. Despite the similarity in the generation capacity, the inclusion of nuclear technology with a total generation capacity of 535.3 MWyr at the end of the study period 2048 has caused coal technology to reduce by 15.5% (536.2 MWyr) from 3,464.4 MWyr for the BaU scenario. At the end of the study period 2048, EFES has initiated the coal requirement to reduce from 56.1% in the BaU scenario to

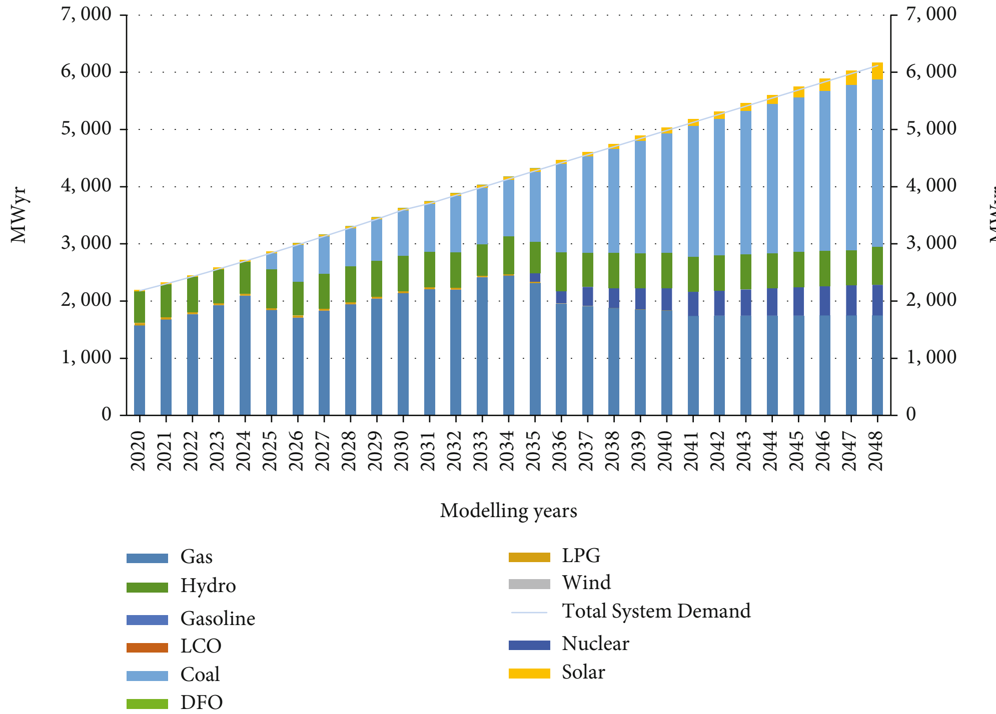

Figure 6: EFES generation per fuel type (MWyr).

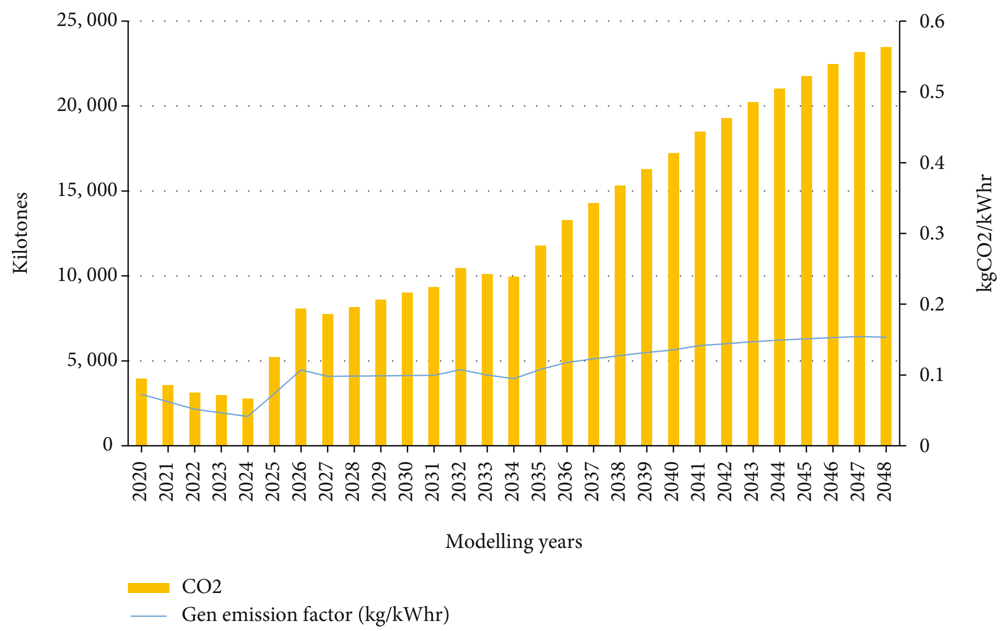

Figure 7: EFES CO_2 and generation emission factor.

47.43%. Meanwhile, all other technologies have maintained their share, in addition to the new generation capacity of nuclear technology.

Figure 7 indicates that, the total CO_2 emissions on the EFES system will span from 3,951.02 kilotons in 2020 to 23,472.8 kilotons in 2048 and average CO_2 emissions of 12,462.89 kilotons. Compared to Figure 4 of the BaU scenario, the indication is that CO2 emissions are increasing less than proportionately, and by 4,142.20 kilotons at the end of the study period, 2048. The corresponding generation emission factor is expected to increase from 0.07 $kgCO_2$/kWhr in 2020 to 0.15 $kgCO_2$/kWhr in 2048 and an average generation emission factor of 0.11 $kgCO_2$/kWhr on the entire system from 2020 to 2048.

Hence, the introduction of the EFES scenario in Ghana's electricity supply system indicates that at the end of the study period 2048, CO_2 emissions have been reduced by 15% (4,142 kilotons) from BaU 27,615 kilotons to EFES 23,472.8 kilotons.

CO_2 emissions under the EFES at the end of the period 2048 are attributed to the installed fossil fuel capacity of 11,552.09 MW, consisting of 7,366.54 MW and 4,185.55 MW for oil/gas and coal, respectively. As a result of the EFES simulation, the total installed capacity of BaU of fossil fuels would be reduced by 653.02 MW by introducing nuclear capacities.

The situation, therefore, shows how the application of the EFES helps reduce CO_2 emissions as low-carbon energy options such as solar, hydro, and wind are being maintained and the introduction of nuclear in Ghana's energy mix. Therefore, the penetration of renewables and other carbon-free technologies requires a strategic measure of inclusion to mitigate climate change. An analysis that somehow confirms the objective of the Ghana 2019 energy policy draft to include coal and nuclear technologies as key baseload options to augment existing hydropower, but is cautious of the former as a fossil fuel option with concerns about climate change [15].

5. Conclusions

As Ghana is aimed at reducing carbon emissions, the study adopted a 15% reduction in CO_2 emissions in the electricity sector. Estimating CO2 emissions from fossil fuel power plants by applying an emission reduction strategy termed EFES has proven to be essential for reducing emissions from the power sector. Thus, the study's power system modelling revealed that including zero-emitting energy sources is key to reducing CO_2 emissions in Ghana's power sector. It was also revealed that CO_2 emissions from all electrical systems are attributed to the type of fuel used for power generation. The study's strategy to curtail electricity generation emissions affects coal and liquid fuels while favouring nuclear and gas generations in the long term. Despite a minimal decrease in rate, comparing the EFES scenario with the BaU scenario or the reference case at the end of the study period 2048 indicates that, CO_2 emissions and the generation emission factor were reduced by 15% (4,142 kilotons) and 69.92% (0.36 kgCO_2/kWh), respectively. For this reason, it is imperative to develop and implement optimal energy mix strategies that will exploit the maximum potential of zero-emitting energy sources while maintaining strong economic growth for Ghana.

Although it will be expensive to mitigate climate change-related issues in the power sector by curtailing CO_2 emissions, reducing emissions will go a long way toward saving the nation from emission-related issues that seriously affect the environment and human health. Therefore, strategic measures are required to include low-carbon energy sources in Ghana's energy mix.

The results of this research are expected to influence decision-making by incorporating climate justice into policies and sectoral activities to achieve sustainable and resilient energy production in a clean environment. Further research is also needed to ascertain the cost of emission reduction strategy on power systems while maintaining the objective of Ghana's economic ambitions.

Data Availability

The Energy Commission of Ghana provided the projection data of the electricity demand that served as the exogenous input variable for the MESSAGE model of the study. As such, the data was not to be disclosed.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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