

UNIVERSITY OF GHANA
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**MODELLING ENERGY SUPPLY OPTIONS FOR LONG-
TERM ELECTRICITY GENERATION - A CASE
STUDY OF GHANA POWER SYSTEM**

BY

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DECLARATION

This thesis is the result of research work undertaken by Mark Amoah Nyasapoh under the guidance of my supervisors towards the award of the Master of Philosophy (MPhil) degree in Economics at the Department of Economics, University of Ghana.

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DEDICATION

I dedicate this work to the Almighty God who has made it possible for me to go through this programme successfully.

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ABSTRACT

Electricity continues to be a major contributor to the development of the economy of every country, Ghana not exempted. There is, therefore, growing interest to ensure that the supply of electricity meets the demand in all sectors of the Ghanaian economy. The economic costs and environmental issues underpinning electricity is, however, a huge bottleneck to the aspirations of Ghana as a country.

The study seeks to explore a long-term (2018 to 2048) comprehensive energy supply strategy to meet the future electricity demand in a sustainable manner while maintaining a low carbon environment. The study employed the development of scenarios, Business As Usual (BAU), and High Economic Growth (HEG) and an empirical methodology that aided the setup of the optimized objective function for the electricity supply model under a set of constraints that define the feasible region containing all possible solutions of the problem.

The results indicate that thermal power plants dominated Ghana's installed capacity. Hydropower plants put together, however, dominated in the electricity generation mix in Ghana during the study period. The introduction of Nationally Determined Contributions (NDC) of 15% and 30% emission reduction targets, showed that hydro and renewables such as wind will make an outstanding increase in electricity generation from 2021 to 2047. The least-cost modelling results concluded that meeting final electricity demands without consideration for environmental impact concerns are the cheapest. Hence, a 30% emission reduction target requires the highest investment for electricity generation throughout the modelling period.

The study recommends that research studies such as this be encouraged for effective energy planning since energy planning studies are limited in the country.

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LIST OF ACRONYMS

| | |
|-----------------|---|
| 3E | Energy, Economic and Environmental models |
| BAU | Business-As-Usual |
| CCGT | Combined Cycled Gas Thermal |
| CCGT | Combined Cycle Gas Turbine |
| CGT | Conventional Gas Turbine |
| CIE | Compagnie Ivoirienne d'Electricité |
| CO ₂ | Carbon dioxide |
| DFO | Diesel Fuel Oil |
| ECG | Electricity Corporation of Ghana |
| EDMCW | Electricity Division of the Ministry of Communication and Works |
| ERP | Economic Recovery Program |
| FPSO | Floating Production, Storage and Offloading |
| GDP | Gross domestic product |
| GHG | Greenhouse Gasses |
| GRIDCO | Ghana Grid Company |
| GSGDA 2 | Ghana Shared Growth Development Agenda II |
| GT_PP | Gas Thermal Power Plant |
| HEG | high economic growth scenario |
| HFO | Heavy Fuel Oil |
| IAEA | International Atomic Energy Agency |
| IDA | International Development Agency |
| IEA | International Energy Agency |
| IIASA. | International Institute for Applied Systems Analysis |

| | |
|----------|---|
| INDC | Intended Nationally Determined Contribution |
| LCO | Light Crude Oil |
| LEAP | Long-range Energy Alternatives Planning |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MARKAL | Market Allocation model |
| MDGs | United Nations Millennium Development Goals |
| MESSAGE | Model for Energy Supply Strategy Alternatives and their General Environmental Impact |
| MoE | Ministry of Energy |
| MW | megawatt |
| NDC | Nationally Determined Contribution |
| NDPC | National Development Planning Commission's |
| NEPG | National Energy Policy, Ghana |
| NES | National Electrification Scheme |
| NG | Natural Gas |
| O&M | Operation and Maintenance |
| OECD | Organisation of Economic Corporation and Development |
| OSeMOSYS | Open source energy modelling system |
| PPP | Public Private Partnership |
| RD&D | Research, Development and Demonstration |
| RES | Reference Energy System |
| SAP | Structural Adjustment Program |
| SGN | Sankofa-Gye Nyame |
| SNEP | Strategic National Energy Plan |

| | |
|---------|--|
| Tcf | Trillion cubic feet |
| TEN | Tweneboa, Enyenra and Ntomme |
| UAE | United Arab Emirates |
| UN-DESA | United Nations Department of Social and Economic Affairs |
| UNDP | United Nations Development Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VRA | Volta River Authority |
| WAGP | West African Gas Pipeline |
| WAPP | West African Power Pool |

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The electricity sector for Ghana has for some time now been faced with power supply challenges, resulting in a significant impact on the Ghanaian economy (Kumi, 2017). There exist a growing public interest in policies that provide the most effective strategies for energy supply sustainably in the country (Aryeetey, 2005; Kumi, 2017; Mundaca, & Neij, 2009). Ghana's anticipated increase in the supply and use of electricity to boost its socio-economic development can have adverse social and environmental impacts depending on the electricity supply option (Aryeetey, 2005). Hence, the current situation of the electricity sector in Ghana requires a long-term electricity study and planning, leading to the appropriate choice of electricity supply options at the optimal level. The use of bottom-up energy, economic and environmental (3E) models based on predictions of energy efficiency policies has gained extensive recognition by policy-makers (Mundaca, & Neij, 2009). Models built on the basis of energy, economic and environment are of prime importance to supporting energy planning studies. Such models also assist in the appropriate planning of policies by assessing the capability of attaining the impacts that would justify the choice and application of energy options for electricity generation (Mundaca, & Neij, 2009). Electricity sector planning must ensure energy linked policies and decisions regarding their investment consider all potential power supply options (Aryeetey, 2005; Ouedraogo, 2017). This is key for developing nations such as Ghana.

The 2010 Ghana National Energy Policy clearly guides the development and management of the country's energy sector. The generation of electricity in Ghana

went through several phases: beginning with diesel generators and stand-alone electricity supply systems owned by industrial mines and factories (Aryeetey, 2005; Eshun & Amoako-Tuffour, 2016; Kumi, 2017). The hydro stage followed with the construction of the Akosombo dam in 1966, and the current additions of thermal-powered technologies that use either gas or light crude oil (Aryeetey, 2005; Gyamfi, Modjinou, & Djordjevic, 2015; Eshun, & Amoako-Tuffour, 2016; Kumi, 2017). The electricity sector, in general, has huge potential to grow with the transformation of the economy through industrialization (National Energy Policy, Ghana (NEPG), 2010; Kumi, 2017; Fenny, 2017; Johnson, Muhoza, Osano, Senyagwa, & Kartha, 2017; Cobbinah, & Adams, 2018). The Government of Ghana aims at a developmental agenda to achieve macroeconomic stability, transform the Ghanaian economy to middle-income status and ensure universal access to electricity by 2020 (NEPG, 2010; Eshun & Amoako-Tuffour 2016; Kumi, 2017). Meeting this fundamental goal requires the country's electricity supply to grow significantly. The challenge in achieving this goal is how to adequately supply electricity, ensure reliability, affordability and in addition widen the electricity infrastructure in Ghana in a sustainable manner in a low carbon environment (Gyamfi, Modjinou, & Djordjevic, 2015; Eshun & Amoako-Tuffour, 2016). In addition, inadequate infrastructure, access to electricity services, high cost of fuel (oil and gas) for the supply of electricity and the vulnerability to climate change and environmental impacts also pose a challenge (Eshun, & Amoako-Tuffour, 2016).

Modelling long-term energy supply options for electric power supply became an essential tool for policy analysis that helps offset the challenges in the energy

sector. Messner (1997) mentioned that the construction of such models was developed with two main goals in the early 1970s when oil price shocks made energy a key focus of attention. The primary reason was to minimise the reliance on expensive imported oil and secondly was to assess the effect of several energy policies on the economy (Messner, 1997). In addition, the application of energy-related models in the late 1980s further moved towards the subject of global warming (Messner, 1997).

Ghana, like many other African economies, has huge energy endowment for electricity generation and the progress made in the establishment of Regional Power Pools such as the West African Power Pool (WAPP) over the last decade is enormous (Castellano et al., 2015). Nonetheless, the optimal supply and access to electricity power and networking in Africa are still underdeveloped with inadequate generation systems (Castellano et al. 2015). Data from the Energy Commission and the Volta River Authority indicated that Ghana's 2018 installed electricity capacity stands at 5,044.56 MW, out of which, 1,579 MW is from hydro generation, 3442.96MW from thermal and 22.6 MW from renewables, mainly solar. Mitigating carbon emissions by means of alternative power generating plants has been an addition to the major challenges being faced. As the Ghanaian economy continues its evolution to attain an efficient and lower electricity intensive future, a time frame of planning not less than 30 years in the power sector is much desired. Therefore, strategic long-term studies for planning has to be a major concern to Ghana.

Hence, the research employs data on 39 energy technologies for electricity supply in Ghana spanning the period 2018 to 2048 through the use of the Model for Energy

Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) to determine the long-term optimal electricity generation mix for Ghana.

1.2 Statement of Research Problem

Issues of electricity planning have become more complex due to the many objectives resulting from the major concern about capital investment and the environmental impact it has on economic development in Ghana. There exists a major gap between developed and developing nations with respect to long-term planning for least-cost electricity generation and socioeconomic development. The demand for electricity in Ghana has increased remarkably, outweighing supply for the past two to three decades (Aryeetey, 2005). In addition, the increase in electricity demand has led to a rapid increase in the level of CO₂ emissions associated with power supply from fossil fuel combustion (Banos et al., 2011).

The above challenging issues are subjects that have been at the forefront of Ghana's electricity sector that has impacted negatively on economic growth and development. The Ghana Energy Policy (2010) categorically stated that Ghana's energy challenge hinges on how to increase electricity supply in efficient capital investment. In addition, the investment of energy supply options for electricity generation is required to be sustainable in a friendly environment.

The benefits of long-term electricity planning are already evident in developed countries such as Japan, Sweden, South Korea, United States of America (USA) and Australia who plan their energy supply for 30 to 50 years ahead (Asif, & Muneer, 2007; Gustavsson et al., 2011; Morrison, et al., 2014). The increasing interest in long-term energy planning for periods beyond 30 years (Asif & Muneer,

2007; Gustavsson et al., 2011; Morrison et al., 2014), has shifted the development agenda of such developed countries far ahead of Ghana, as a developing nation.

Ghana on the other hand of the development ladder has for some time not paid attention to periods beyond 15 years as long-term development planning studies in the electricity sector. Ghana's first Strategic National Energy Plan (SNEP) was for the period 2006 to 2020 (Dramani, J. B. & Tewari, D. D. 2014; Energy Commission, 2006). Electricity generation and supply planning are therefore key for national development in terms of capital investment and environmental concerns. The capital investments normally involve a substantial risk that cannot be reversed once undertaken due to long lifetimes and many substitutes of power generation (Bean, & Hoppock, 2013). The long-term (30 years and beyond) planning for developed nations as against Ghana's 15 years of national energy planning makes it worrisome.

In 1966, Ghana had 512 MW from hydro generation and diesel generators all over the country that gave sufficient power for institutional and residential uses (Lungu, N., 2015). The Akosombo Hydro Electric Power project became a comprehensive planned industrial, agricultural, and service industry "take-off" initiative for the fast-track development of Ghana (Lungu, 2015). This development was in harmony with the vision of a long-term development plan in the country's electricity sector and for the African region as a whole (Lungu, 2015).

Aside the earlier development plans in the electricity sector, Ghana made several attempts for the past decades to increase rural electrification schemes alongside major electrification projects but failed to develop credible alternative power facilities to augment such attempts. In effect, for over 52 years now, the combined power-generation output of increasing Ghana's power generation capacity is

5,044.56 MW in 2018 (Energy Commission, 2018; VRA, 2018). However, the demand for power in Ghana has more than quadrupled, population alone having increased over three-fold, from approximately 8 million in 1966 to over 28 million in 2018. A deduction of Akosombo's 1,020 MW current installed capacity from the total of 5,044.56 MW gives a net generating capacity, during the 52 years. Sailing on the success of the Akosombo Dam project, Ghana's days of reckoning begun in 1983, thirty-five (35) years ago. This led to the persistent acute rolling blackouts (load-shedding) in Ghana, popularly known in the local Ghanaian language as "Dum-Sor".

In an effort to address the country's energy supply options for electricity generation, the study will explore a long-term (30years) plan for electricity supply with the least cost generation options. The long-term supply plan will satisfy both the socio-economic and environmental issues that will aid government-based policies.

1.3 Objectives of the Study

The main objective of the study is to explore a long-term (2018-2048) comprehensive energy supply strategy to meet the future electricity demand in a sustainable manner while maintaining a low carbon environment. In achieving this objective, the following specific objectives would be adopted:

First, evaluate the long-term electricity generation mix and their Carbon dioxide (CO₂) emissions.

Second, determine the Country' long-term supply strategy based on least-cost of various generating plants.

Finally, estimate electricity system investments and the cost associated with projected additional power plants (i.e the financial impact of new capacities on Ghana's economy).

1.4 Research Questions

The topic incites a number of research questions, these include the following:

To begin with, how effective can the energy supply options (resources) for Ghana be used to generate electricity for end-use amidst a low carbon environment?

Secondly, what is Ghana's long-term electricity supply mix plan and the corresponding Carbon dioxide (CO₂) emissions generation?

Lastly, what is Ghana's long-term electricity supply strategy based on generation and investment costs of electricity generation?

1.5 Justification of the Study

Electricity is an important input in the manufacturing of goods and services across all economic sectors of Ghana. It is similarly important to the provision of basic civic services in improving access to education and eventually to raising incomes (Aryeetey, 2005; IAEA, 2008). The resilient supply of electricity is a key component in Ghana's national development. The country's industrialization aspirations would best be achieved with sufficient, affordable and reliable electricity. However, the gap that existed between electricity planning horizons of many developed countries and Ghana as a developing country is a major bottleneck to economic growth and development. It is therefore imperative for a strategic long-term electricity supply plan and implementation, leading to the appropriate choice of energy supply options for electricity generation at the least cost.

To the effect of electricity on economic development, several empirical evidence confirm the positive relationship between electricity supply or use and economic growth and development (Adom, 2011; Qazi et al., 2012; Ogundipe & Apata, 2013; Ramakrishna & Rena, 2013; Bergasse et al., 2013; Castellano, et al., 2015). Shortages in Ghana's electricity supply (Clerici et al., 2016) have shown that it is necessary for Ghana as a nation to explore all the feasible energy sources to enhance national energy security in a benign environment (Aryeetey, 2005; Ouedraogo, 2017). The attempt to resolve the challenges in the country's electricity sector would require diversifying the electricity generation mix, and this can be done by the use of optimization models that will aid policy decision making (Kumi, 2017).

The supply of electric power to meet the high growing demands is always accompanied by related energy resource availability and environmental aspects of power supply technologies (Ruijven, 2008). The development of energy system models aims to provide insights into designing a sustainable electricity system that effects national energy policies on socioeconomic growth and development while satisfying environmental concerns (Mondal & Mezher, 2017). In addition, the application of energy, economic and environmental (3E) models offer critical insights into public policy in providing the most efficient energy supply options for electricity supply in the long-term (Mundaca & Neij, 2009). Long-term (30 years) projected electricity supply plan for Ghana is expected to have profound socioeconomic, financial and environmental implications for development (Nkonoki & Sørensen, 1984; Toth, 2012).

Issues of energy studies and planning for successive implementation and installation of power plants to supply electricity for consumption comes to play in

the midst of Ghana's electricity crises. Long-term planning for electricity and efficiency are critical if Ghana is to achieve electricity capital investment sufficiency in a low-carbon environment. The challenge of determining the least cost on the investment of electric power supply, generation mix and carbon dioxide (CO₂) emissions associated with power plants (Anderson, 1972) has motivated this study in Ghana. Long-term (30 years and above) studies and planning in the electricity sector is key to allow for a reviewed short to medium term basis for current updates and relevant for implementation. The study is a long-term model plan defined on the basis of current power generation cost, technologies, international fuel prices, amongst other basic assumptions (Asif & Muneer, 2007), that will aid effective planning and cost in Ghana's electricity sector.

1.6 Outline of the Study

The study is made up of six chapters laid out in the following manner:

Chapter one presents the background to the study, provides the statement of the research problem, the main objective of the research alongside the specific objectives to attain the main objective and the significance of this research. Chapter two presents an overview of energy supply options for electricity generation, including reforms and policies that are needed to guide the sensitivity analysis of the study. Chapter three reviews the literature, summarizing the existing theoretical and empirical literature on the concept of energy modelling for long-term electricity supply. Chapter four provides the methodology of the study. The results are reported and discussed in chapter five. Chapter six summarises the findings, concludes the paper and make policy recommendations. Limitations of the study and recommendations for future studies have also been discussed.

CHAPTER TWO

OVERVIEW OF ELECTRICITY SUPPLY IN GHANA

2.0 Introduction

The National Development Planning Commission (NDPC) of Ghana envisages a high economic development over the next forty years (UNDP, 2017). Growth is expected to increase from about US\$ 46.0 billion in 2018 to about US\$ 1,370 billion by 2047 at an average annual rate of 11.8%. This ambitious growth requires a high growth in electricity supply. Studies conducted on the shortages of Ghana's electricity supply (NEPG, 2010; Clerici, et al, 2016) have shown that, Ghana needs to explore and develop all feasible energy sources such as oil, gas, renewables, coal and nuclear to enhance national energy security in a benign environment (Aryeetey, 2005; NEPG, 2010). Even as electricity use promotes socio-economic development, it, on the other hand, can be associated with adverse environmental and social impacts (Aryeetey, 2005). The supply of electricity to meet the high growing demands is always accompanied by the environmental impacts of power generation (Ruijven, 2008). The electricity supply sector in Ghana had seen numerous reforms over the past decades. The key importance of the sector has triggered several policies regarding energy supply options needed to supply electricity at the optimal level through a number of technologies. The optimal and effective use of energy supply options such as oil and gas for electricity generation is crucial for the promotion of social well-being as well as the development of modern economies (Ayres, Turton, & Casten, 2007; Holdren, 2007; Kaygusuz, 2012). Ghana's electricity consumption since the early 1960s contributed for about 7 - 15% of total final energy demand (Aryeetey, 2005). However, the country's electricity generation does not have a plan for implementation that ensures long-

term electricity generation and carbon free environment. It is therefore essential to make appropriate energy choices for electricity supply in the medium to long-term with key attention to environmental, social costs and economic benefits (IAEA, 2008). This chapter presents an overview of Ghana's electricity generation for the past decades focusing more on electricity sector policies and reforms.

2.1 Electricity Sector Development Policies

The electricity sector development policy during the first stage of Ghana's energy policy development was for the exploitation of Indigenous Hydropower Resources for Electricity Generation (Energy Commission, Ghana, 2006). In the early 1960s, electricity was supplied by the Electricity Division of the Ministry of Communication. The electricity supply was from about 20 isolated diesel generators to limited industrial, commercial and residential consumers in some few urban settlements. Some mining and related companies also generated electricity from diesel generators for their own internal use. It was estimated in 1960, that about 6% to 6.6% of the Ghanaian population had access to electricity (Electricity Division of the Ministry of Communication and Works (EDMCW), 1960). To further complement the country's first diesel generator, the Government of Ghana in 1961 established the Volta River Authority (VRA) with the mandate to develop the hydropower resources on the Volta River for electricity generation and address the environmental impacts on the towns and people living along the lake displaced due to the creation of the Volta Lake (VRDA, 1961) (Cobbinah, & Adams, 2018). In 1965, a 588 MW Akosombo Hydropower plant was completed and upgraded to 912 MW in 1972. In 1982, a 160 MW Kpong Hydropower plant, 40 km downstream from the Akosombo Hydropower plant was completed. In an effort to

increase generation capacity, the economic feasibility of the Bui Hydropower project was reviewed in 1980. However, efforts to mobilize funds to undertake the project proved futile. Hence, as of 1982, the total hydropower generation capacity for Ghana was 1,072 MW. Electricity Corporation of Ghana (ECG) took over from the Electricity Division in 1967. They had about 15 diesel generation stations in rural settlements as at 1983. The price of electricity set below the cost of supply and the eventual decrease in government subventions led to a severe disorder of much of the electricity distribution infrastructure especially towards the end of 1982's.

Electricity sector development policies that took place between 1983 and 1993 focused on the expansion of generation capacity and diversification of generation mix, retrofitting and modernizing electricity generation facilities and the implementation of the national electrification scheme. Ghana's electricity generation from hydropower sources suffered a severe setback due to drought in 1983 and 1984. The situation exposed the risk of Ghana's over-dependence on hydropower generation. A study by Acres International Limited, completed in 1985, identified thermal power generation based on natural gas, as the least cost power generation option (GGPS-VRA, 1985). However, due to the absence of natural gas supply for thermal power generation, VRA in 1991 commissioned a study of the hydropower possibilities on the White Volta, Red Volta and Oti tributaries of the Volta River. The high cost of generation from these hydropower options left VRA to opt for thermal power generation based on light crude oil. The Akosombo Hydropower plant retrofit started in 1991 but was suspended in 1995 to avoid further capacity shortage due to poor inflows into the Volta Lake (VRA,

1995). The government of Ghana sought to electrify the whole country especially the rural areas to promote small to medium-scale cottage industries and enterprises, following the economic downturn and the implementation of the Economic Recovery Program (ERP) in 1983 (Essays, U K., 2013). In addition, extending electricity to all parts of the country was to help provide modern basic social services such as health, education, water, etc to stimulate employment generation and improve living conditions. It was estimated in 1989 that, only 478 communities out of 4,221 in the country had been connected to the national grid (Acres International, 1991). This led to the government of Ghana in 1989 to initiate a National Electrification Scheme (NES) as the principal instrument for extending electricity supply over a thirty year period from 1990 to 2020 to include all communities with a population above 500 in the country (Global Network on Energy for Sustainable Development (GNESD), 2007; Ministry of Energy (MoE), 2010). As a result of the NES, electricity coverage increased from about 19% in 1983 to about 31% in 1993 and 82.5% in 2016 (Ministry of Power, 2016)

The electricity sector development policy for the period 1994 to date, focused on the expansion of capacity generation and diversification of the electricity generation mix. The VRA in 1998 resumed work on the Akosombo Generating Station Retrofit Project which was suspended in 1995. The retrofit project completed in 2005, increased the plant efficiency, prolonged the life-span and upgraded the capacity of the plant from 912 MW to 1020 MW. In addition, the government of Ghana in 1998 entered into an agreement with Compagnie Ivoirienne d'Electricité (CIE) of Cote d'Ivoire to import up to about 250 MW of electricity to supplement domestic generation in order to meet the increasing

electricity demand. In an effort to further increase the domestic generation capacity, VRA in 1998 developed a 330 MW capacity thermal plant based on light crude oil. In 2001, VRA again entered into a joint venture with CMS Energy of United States and developed 220 MW capacity thermal power plant also based on light crude oil. These thermal plants were expected to switch to cheaper natural gas when the West African Gas Pipeline became fully operational in 2010. The government added a 400 MW Bui Hydropower plant on the Black Volta, in December 2013. Additional power plants were added to enable Ghana's generation capacity to meet the increasing electricity demand. As at the year 2018, Ghana's dependable electricity generation capacity stood at 5,044.56 MW (Energy Commission, 2018, VRA, 2018).

The implementation of the sector planning for electricity supply has become a major challenge to the industry from 1960 to date. The reforms that led to the development of the electricity sector policies are discussed.

2.1.2 Electricity Power Sector Reforms in Ghana

The government of Ghana in 1994 initiated the process to reform the electricity sector devoid of public monopoly, promote competition and improve operational efficiency through the accountability of management in the public sector utilities and attract private sector participation (Edjekumhene et al, 2001; Nyarko, B. J., et al., 2011).

The electricity sector reform in Ghana was taken to accomplish a World Bank conditionality of an International Development Agency (IDA) credit facility granted to the government of Ghana to build the 330 MW thermal power plant at

Aboadze (Nyarko, B. J., et al., 2011). The first step in reforming the power sector was commercializing the operation of energy sector utilities. The Electricity Corporation of Ghana in February 1997 was converted into Electricity Company of Ghana (ECG) to fulfil a commitment the government of Ghana made to the World Bank under the ERP/ Structural Adjustment Program (SAP) in the early 1980s. As part of the reform process, Ghana's two electricity distribution utilities (ECG and NED) were to be merged and later split into five strategic business units or concession zones to compete among themselves and operate in a regulated electricity market where the maximum demand of a customer will not exceed 5 MW (Edjekumhene et al, 2001; Nyarko, B. J., et al., 2011).

In addition, the government of Ghana was expected to create a de-regulated or Wholesale Power Supply Market where customers will be free to choose their electricity supplier, negotiate and enter into contracts for the purchase and supply of their electricity. The reform process gave the opportunity to the power producers to trade among themselves and sell power to distribution companies, major consumers, intermediaries or the wholesale market (Nyarko, B. J., et al., 2011).

2.2 Current and Future Energy Resources and Fuel Supply for Electricity Generation

Ghana has enormous energy resources that have been tapped on several occasions for electricity generation. This included but not limited to the huge volumes of water, natural gas, oil and renewable sources.

Ghana as a country has a number of rivers and streams with suitable hydropower potential. The hydropower potentials in the country have been classified into non-renewable (capacity exceeding 100 MW) and renewable (capacity less than 100 MW) categories. Renewable hydropower systems are classified into large, medium, and small-scale systems. Table 2.1 presents the capacity and the average generation of the hydropower systems in the country.

Table 2.1: Hydropower Potentials

| Hydropower systems | Capacity range (MW) | Number of Sites | Total Capacity (MW) | Average Generation (GWh) |
|-----------------------|---------------------|-----------------|---------------------|--------------------------|
| Non-renewable | More than 100 | 3 | 1,580.0 | 6,300.0 |
| Renewable | Less than 100 | 38 | 838.8 | 3,545.9 |
| Large-scale | Between 10-100 | 16 | 837.0 | 3,544.0 |
| Medium-scale | Between 1-10 | 0 | 0 | 0 |
| Small-scale | Less than 1 | 22 | 1.8 | 1.9 |
| Total Hydro-Potential | | 41 | 2,418.8 | 9,845.9 |

Source: Energy Commission, 2016

The country's total hydropower potential has been estimated to be about 2,420 MW, of which 65.3% of this potential (i.e. 1580 MW), has been exploited. These are the 1,020 MW Akosombo Hydropower Plant with a dependable capacity of 900 MW and the 160 MW Kpong Hydropower Plant with a dependable capacity of 148 MW, all on the Volta River. The third is the 400 MW Bui Hydropower Plant with a dependable capacity of 342 MW on the Black Volta River. There exist Mini-Hydroelectric Power system in Ghana but untapped that is estimated to be 840 MW. The Mini-Hydroelectric Power Plants, when exploited, could yield a dependable capacity exceeding 500 MW (Togobo, 2011).

In 2007, crude oil associated natural gas was discovered in the Jubilee Fields, offshore Cape Three Points in the country's sedimentary basins. Natural gas was

again discovered in the Tweneboa, Enyenra and Ntomme (TEN) and Sankofa-Gye Nyame (SGN) fields. The total associated and non-associated natural gas reserves-in-place discovered increased from 0.57 trillion cubic feet (Tcf) in 2010 to about 2.38 Tcf in 2014, a four-fold increase. It is assumed that if 80% of the country’s natural gas reserves-in-place is recovered for electricity generation, it would be adequate to generate 1,200 MW electricity for about 25 years from a combined cycle power plant with a heating rate of 7,800 BTU/kWh. Table 2.2 shows the reserves and other features of the associated and non-associated natural gas fields discovered for Ghana.

Table 2.2: Natural gas discoveries and reserves

| Natural Gas Fields | Associated Gas in-place (BCF) | Non-Associated Gas-in-place (BCF) | Year of discovery | Year of start production | Year of the end of production | Expected Peak daily production (mmscf/day) |
|--------------------|-------------------------------|-----------------------------------|-------------------|--------------------------|-------------------------------|--|
| Jubilee | 568 | 0 | 2007 | 2015 | 2022 | 100 |
| TEN | 294 | 59 | 2009 – 2012 | 2016 | 2027 | 85 |
| SGN | 287 | 1071 | 2009 -2012 | 2016 | 2038 | 180 |

Source: Energy Commission, 2016

A major challenge that accompanies Ghana’s reliance on domestic gas for electricity generation is the irregular natural gas supply from the Jubilee Field due to frequent shut-downs of the Floating Production, Storage and Offloading (FPSO) and Atuabo gas processing plant.

Ghana made importation of natural gas from Nigeria to supplement the country’s gas production for electricity generation. Experts, however, put Nigeria’s natural gas reserves at about 110 Tcf and some even put it as low as 47 Tcf if strict commerciality criteria are applied (Santley, Schlotterer, & Eberhard, 2014). Figure

2.3 shows annual light crude oil and natural gas imports and the prices of these fuels to Ghana.

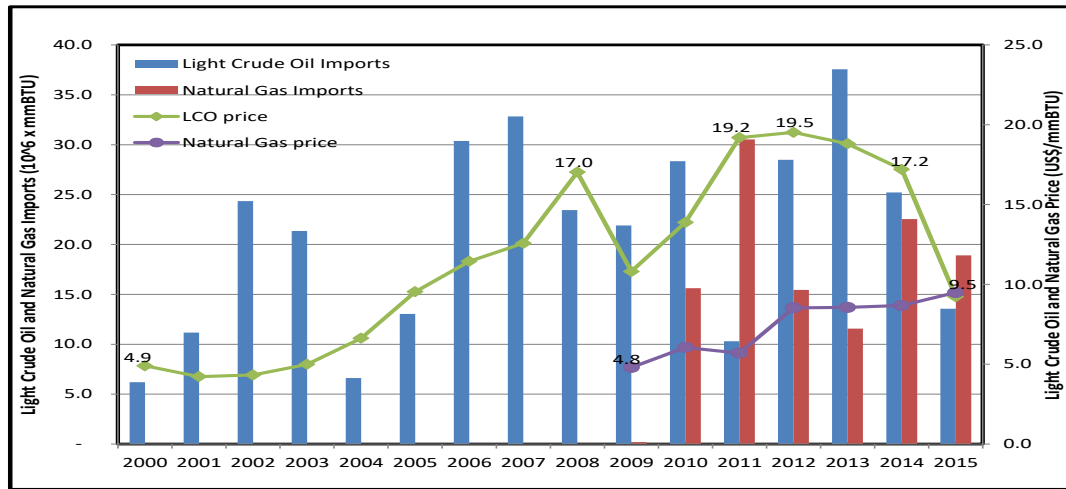


Figure 2.1 Annual light crude oil and natural gas imports and their price

Source: Energy Commission, Ghana 2016

Some challenges were further associated with the purchase of fuels for electricity generation in Ghana from 2000 to 2016. These included but not limited to the increase in average price of light crude oil from US\$ 4.9/mmBTU in 2000 by 250% to US\$ 17.0/MMBtu in 2008. It then decreased in 2009 before increasing to an all-time high of US\$ 19.5/mmBTU in 2012. The price has, however, decreased thereafter to US\$ 9.2/MMBtu in 2015. Imported natural gas price also almost doubled from US\$ 4.5/mmBTU in 2009 to US\$ 9.5/MMBtu in 2015. In addition, natural gas supplies from the West African Gas Pipeline (WAGP) since 2012 have been erratic and inadequate leading to periodic generation shortfalls of about 500 MW in 2015 and associated power supply crises (Energy Commission of Ghana, 2016).

These developmental issues exerted upward pressure on electricity tariffs and the cost of goods and services in Ghana (Kumi, 2017). Due to the existing challenges,

it was estimated that domestic demand for natural gas will outstrip supply from domestic fields and imports through WAGP by 2025 (Mathrani et al 2013).

Ghana's electricity potential from renewables ranging from rooftop solar generations to the wind and solar power plants is much encouraging. The solar irradiation of Ghana ranges from 4.5-6.0 kWh/m²/day, with the northern part of Ghana recording the highest levels. The amount of sunshine usually ranges from 1,800 to 3,000 hours annually (Togobo, 2011; RECP, 2018). Ghana currently has an operational solar installation of 170 MW, from BXC, VRA Navrongo Solar and Savannah as at 2018. The wind potential for the country is estimated to have on the average annual wind speeds of 4-6m/s at 50m above sea level along the coast and on some islands. Wind resource assessments conducted at eight sites along the coast between 2011 and 2013 indicated average monthly wind speeds at 60m elevation. This shows the potential for development of around 300 MW of wind farm capacity in Ghana (RECP, 2018). Ghana is currently expecting a 225 MW capacity of wind power from Upwind Ayetepa in 2020.

Coal and nuclear power technologies have been envisaged to be developed as energy options for electricity generation in the long-term. In spite of its serious environmental impact, coal still remains the world's number one fuel source for electricity generation (World Coal Association (WCA), 2013). The reliance on coal power generation is partly due to the relative ease of supply of coal and its ability to follow the market and increase or decrease output as against the price volatility of other fossil fuels (World Energy Council (WEC), 2016). Ghana in 2015 considered the addition of two 350 MW power plants of coal generation (Shenzhen Energy & VRA, 2015). This, however, did not materialise due to reasons such as

environmental concerns. Ghana, for some time now has been working on the use of nuclear technology for power generation, despite public perception about the risk it poses in terms of accidents (Nyarko B J B, et al. 2011). The nuclear technology for power generation is seen as a key factor in boosting a country's economic fortunes in terms of job creation and stable power delivery. The fuel for nuclear power technology is considered to be cheap, constituting about 14% of the entire electricity generation costs, compared to 89% in gas and 78% in coal (Lovins, 1976).

2.3 Electricity Power Supply in Ghana

2.3.1 Electricity Generation in Ghana

Ghana's electricity generation has increased steadily over the past decades but the demand has outweighed the supply. The total electricity made available for gross transmission almost doubled from 7,223 GWh in 2000 to around 13,700 GWh in 2016 (Energy Commission, 2018). The total installed electricity capacity more than doubled, increasing from 1,418 MW in 2000 to 5,044.56 MW in 2018 ((Energy Commission, 2018; VRA, 2018). The development of electricity generation power plants, their installed and dependable generation capacities in 2000, 2010 and 2018 are presented in Table 2.3.

| Power Plant | Fuel Type | 2000 | | | 2010 | | | 2018 | | |
|-------------------------|-----------|-------------------------|---------------------|-------------------------------|-------------------------|--------------------------|-------------------------------|-------------------------|--------------------------|-------------------------------|
| | | Installed Capacity (MW) | Dependable Capacity | % of Total Installed Capacity | Installed Capacity (MW) | Dependable Capacity (MW) | % of Total Installed Capacity | Installed Capacity (MW) | Dependable Capacity (MW) | % of Total Installed Capacity |
| Akosombo | Hydro | 788 | 700 | 66.85 | 1020 | 900 | 54.43 | 1020 | 900 | 31.30 |
| Kpong | Hydro | 160 | 148 | | 160 | 148 | | 160 | 140 | |
| Bui | Hydro | 0 | 0 | | 0 | 0 | | 399 | 340 | |
| Sub-total | | 948 | 848 | | 1180 | 1048 | | 1579 | 1380 | |
| Takoradi T1 | LCO/Gas | 330 | 300 | 33.15 | 330 | 300 | 45.57 | 340 | 300 | 68.25 |
| Takoradi T2 | LCO/Gas | 110 | 100 | | 220 | 200 | | 330 | 320 | |
| Tema TT1 | LCO/Gas | 0 | 0 | | 110 | 100 | | 110 | 100 | |
| Tema TT2 | Gas | 0 | 0 | | 48 | 45 | | 49.5 | 45 | |
| CENIT | LCO | 0 | 0 | | 0 | 0 | | 110 | 100 | |
| MRP | Gas | 0 | 0 | | 80 | 40 | | 80 | 0 | |
| Tema Diesel | Diesel | 30 | 20 | | 0 | 0 | | 0 | 0 | |
| Sunon Asogli(SAPP_1) | Gas | 0 | 0 | | 200 | 180 | | 200 | 180 | |
| Sunon Asogli_2 (SAPP_2) | LCO/Gas | 0 | 0 | | 0 | 0 | | 360 | 320 | |
| Kpone (KTPP) | DFO | 0 | 0 | | 0 | 0 | | 200 | 150 | |
| Karpower Ship 2 | HFO | 0 | 0 | | 0 | 0 | | 495 | 450 | |
| AMERI 2016 | Gas | 0 | 0 | | 0 | 0 | | 250 | 230 | |
| AKSA | HFO | 0 | 0 | | 0 | 0 | | 375 | 250 | |
| CEN Power | NG/LCO | 0 | 0 | | 0 | 0 | | 340 | 300 | |
| Trojan Energy | NG/DFO | 0 | 0 | | 0 | 0 | | 24.96 | 24.96 | |
| GP Tarkwa | LPG | 0 | 0 | | 0 | 0 | | 35.58 | 33 | |
| Trojan 3 | NG | 0 | 0 | | 0 | 0 | | 49.92 | 49 | |
| Trojan Tema | DFO | 0 | 0 | | 0 | 0 | | 16.25 | 16.25 | |
| Trojan Kumasi | DFO | 0 | 0 | | 0 | 0 | | 16.25 | 16.25 | |
| GP Chirano | LPG | 0 | 0 | 0 | 0 | 33 | 30 | | | |
| GP Damang | LPG | 0 | 0 | 0 | 0 | 27.5 | 20 | | | |
| Sub-total | | 470 | 420 | | 988 | 865 | | 3442.96 | 2934.46 | |
| VRA Grid Solar PV | Sunshine | 0 | 0 | 0.00 | 0 | 0 | 0.00 | 2.5 | 1.8 | 0.45 |
| Safusana | MSW | 0 | 0 | | 0 | 0 | | 0.1 | 0.1 | |
| BXC | Sunshine | 0 | 0 | | 0 | 0 | | 20 | 18 | |
| Sub-total | | 0 | 0 | | | 0 | | 0 | | |
| Total | | 1418 | 1268 | 100 | 2168 | 1913 | 100 | 5044.56 | 4334.36 | 100 |

Table 2.3: Installed capacity of electricity generation systems

Source: Energy Commission, 2018; VRA Fact Sheet 2018

2.3.2 Electricity System and Supply Challenges in Ghana

Ghana's main objective of the electric power supply system was to ensure security and continuous provision of electricity to meet the country's socioeconomic needs (Khatib, Barnes & Chalabi, 2000). Electricity supply in Ghana has been unreliable over the past three decades, leading to three major nation-wide power crises and rationing exercises for the periods 1993/1984, 1997/1998 and 2006/2007 to 2015 (Eshun, & Amoako-Tuffour 2016), until mid-2017 when it became a bit stable. The power supply shortfalls were mainly attributed to perennial droughts that led to the Akosombo hydropower station to under generation of electricity. The situation was characterized by periodic nationwide power crises as well as localized power outages in the country (Eshun, & Amoako-Tuffour, 2016; Clerici et al. 2016). The perennial droughts compelled a shift to the introduction of thermal power generators in 1997 that run mainly on crude oil, and currently running on a combination of fossil fuel options. Unreliable gas supply from Nigeria has, in turn, plunged Ghana into periodic power shortfalls in recent times (Mathrani et al., 2013). If this continues, future high crude oil and natural gas prices will also serve as a source of risk to Ghana's electricity generation resulting in significant effect in the cost of thermal electricity generation (Eshun & Amoako-Tuffour, 2016). This will, in turn, exert an upward pressure on electricity tariffs and household electricity bills, which is already a significant portion of the average monthly household expenditure in Ghana (Clark, Davis, Eberhard, Gratwick, & Wamukonya, 2005).

As an immediate solution to these crises, efforts have been made to utilize local gas resources from the Atuabo gas project as well as constructing emergency

plants, thereby improving the situation. Ghana as a country through the Energy Commission has made short and medium-term electricity plans (Energy Commission, Ghana, 2006). The scope and content of the electricity sector planning, therefore, need to be shaped for the country to achieve economic growth and prosperity through long-term electricity planning and implementation. This will allow for reliable and affordable electricity available to industry, social services and households.

2.3.3 Long-Term Plans to Deal with Periodic Power Crises in Ghana

The institutional framework for developing comprehensive energy plans in Ghana is in its infancy. Energy-related modelling for electricity power end-use for Ghana began in 2006 with the development of the Strategic National Energy Plan (SNEP). The SNEP was the first energy/electricity planning study for Ghana from 2006 to 2020 (Energy Commission, Ghana, 2006).

In order to deal with the recurring energy crises, the government of Ghana decided to explore and develop alternative power sources, such as renewable, nuclear and coal to enhance energy security. In the case of renewables, two grid-connected solar plants with capacities 2.5 MW and 20 MW have been constructed. There are plans to construct additional solar plants as well as other renewable systems such as wind, mini-hydro, biogas, etc. There were plans to construct two coal plant units with a total installed capacity of 700MW by 2020, and later include additional units with a total capacity of 1,400MW (Shenzhen Energy & VRA, 2015). In the case of nuclear, a Presidential Committee was set up to assess its viability in 2007. A cabinet decision was then taken in 2008 to include nuclear power in the national

energy mix within a decade. Plans are also underway to establish Ghana's nuclear power owner-operator as at 2018.

Arguably, Ghana's energy supply security strategy needs to be focused on developing an optimal electricity supply mix, which balances external, and internal energy sources to achieve long-term economic, social and environmental benefits. In addition, the country's high dependency on hydropower systems over the past four decades has led to establishing the fact that hydropower systems are vulnerable to weather variability or climate change. Hence, to ensure long-term electricity supply security, it is essential to develop an optimal electricity generation mix based on diverse technologies and fuels to fulfil long-term economic, social and environmental intentions.

2.4 Summary

The Chapter outlined the policies and reforms in Ghana's electricity sector since 1960. It also presented electricity generation in Ghana, challenges and long-term plans to deal with power crises. A cast at the prevailing challenges of the electricity sector in Ghana since 1960 makes it desirable for long-term power systems planning and modelling for optimal electricity supply in a low carbon environment.

CHAPTER THREE

LITERATURE REVIEW

3.0 Introduction

This chapter analyses the relevant theoretical and empirical literature on energy supply options for long-term electricity generation. The first section of this chapter deals in brief with energy in general economic theory. The second section deals with the electric power supply in Ghana, followed by the energy resource planning for electricity generation and finally on the energy economic and environmental (3Es) systems modelling.

3.1 Energy in General Economic Theory

Many studies in contemporary times have described economic activity and growth relating to the production function (To H., Wijeweera A. & Charles M. B. 2013). To H. et al. (2013) argued that models of neoclassical growth including Solow's growth model regularly consider labour and capital as the primary factors of production. The mainstream theory of growth thus consider energy to have a relatively small role in economic production (To H., et al. 2013; Solow, 1956). The assumption by neoclassical economists is often that capital and energy are completely interchangeable (To H., et al. 2013; Solow, 1974). The claim under conditions of economic efficiency is that when energy consumption is reduced, it does not result in the reduction of economic growth (To H., et al. 2013). The perception of To H. et al. (2013) indicate that the focus in the economic growth theory is on the primary inputs of production, typically, labour and capital, including land as a subcategory of capital. However, the neoclassical growth model theory has received criticisms from proponents of ecological economics grounded

in the biophysical theory of the role energy plays in economic growth. The viewpoints of several ecological-economists have considered the role of energy alongside the roles of other classical inputs such as capital and labour (To H., et al. 2013; Stern, 2011).

Energy is necessary for economic production that will eventually lead to economic growth, since all forms of production involve the transformation or movement of matter in some way, as applied in the law of thermodynamics (To H., et al. 2013; Lucas, 2002; Galor & Weil. 2000). The integration of the theory of energy on economies has mostly been dealt with by the use of a production function approach. The integration is based on the capital and labour inputs reflected in neoclassical growth theory, energy as discussed in ecological economics models and capital input argued in endogenous growth models (To H., et al., 2013). The key relations between economic growth and energy consumption made the subject an interesting area of research. These mainly focused on the growing dependence of the economy on energy and economic growth stimulating large-scale development and use of energy (To H., et al. 2013). The energy crisis of the 1970s brought about the realisation of energy as an important commodity for GDP growth (Kavrakoğlu, 1987; Messner, S. 1997). The study by Kraft and Kraft (1978) to ascertain the nexus between economic growth and energy further revealed the concept of the impact of energy.

In addition, econometric studies have used several practical forms to assess the elasticities of substitution between capital and energy. The studies revealed that capital and energy are weak substitutes and possibly potential supplements (Stern, 1993; Frondel and Schmidt, 2002)

The discussions above shows that energy is a vital input in the production process since it is used in many economic activities (To H., et al. 2013). In addition, the establishment of neoclassical environmental economics in the 1970s is currently being used for the theoretical understanding of environmental policy instruments (Götz, B., et al., 2012). Environmental economics originated from integrating the environment, represented through environmental commodities such as “clean air”, into the economic system (Fais B. 2015). The objective was to assess the efficient means of allocating scarce resources to the various production processes and manufactured goods to consumers (Fais B. 2015). In addition, welfare economics argued that, under the assumption of competitive markets, free markets automatically ensure a Pareto efficient allocation of resources such as energy (Fais B. 2015; Götz, et al., 2012).

Energy has therefore been a subject of interest to economists and systems analysts for a long time (Kavrakoğlu I., 1987). In addition, the relations between economic activities and energy, exchange of fuels, conservation options and environmental concerns are fresh areas of dimension to energy policy analysts, forecasts and planners (Kavrakoğlu I., 1987). These areas of concern to the economists, systems analysts and mathematicians made it possible to formulate methods of analysis as solutions to complicated problems (Kavrakoğlu I., 1987). Long-term goals such as political or economic independence, technology development, protection of the environment, are factors that call for models specially developed for these purposes (Messner, S. 1997: Kavrakoğlu I., 1987).

3.2 Electricity Supply Optimality for Long-Term Generation

Electricity is a basic input for the provision of goods and services, leading to its essential impact on economic growth and development (Qazi, Ahmed, & Mudassar, 2012). It has been argued that Ghana's quest for sustainable economic development is much dependent on an uninterrupted electricity supply system at the least cost (Clerici et al., 2016). Therefore, the supply of affordable, sufficient and reliable electricity demands a well-planned energy system. Thus, the development of a sustainable energy system that encompasses various aspects of electricity generation is essential (Mondal & Mezher, 2017; Khatib, et al., 2000).

An optimal electricity supply system is made up of various components of energy resources as primary energy, conversion technologies that transform and supply the resources to end-users in the form of secondary energy, and finally, the final electricity demand sectors made up of diverse economic sectors (Nakata, Silva & Rodionov, 2011). Technological development in recent years has been made to reconcile national economic ambitions with assessments of long-term sufficient electricity supply at the optimal level. To complement the set of ambitions, nations require dedicated Research, Development and Demonstration (RD&D) (Messner, 1997). In addition, Seebregts, et al., (1998) pointed out that the successful implementation of electricity supply modelling studies needs the market deployment of optimization models under varying external conditions.

Research developments in the modelling of energy systems that aid policy decision making has become a major focus of long-term electricity supply studies (Messner, 1997). Models of electricity supply are concerned with the determination of the

least-cost options of power generation system that meets demand, subject to a number of constraints. The structure of such models, in general, makes use of optimization or simulation methods. The optimization usually follows linear and non-linear programming (Hainoun et al., 2010; Mondal & Mezher, 2017). A number of the supply models have extensions that include extra structures to calculate the impacts on the planned energy system (Hogan, 2002). The development of such models was initiated during the oil price shocks and global warming in the early 1970s and late 1980s, respectively (Messner, 1997). A representative of optimal energy supply models include, but not limited to Market Allocation (MARKAL) model generator; PRIMES Energy System Model; Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) and the Long-range Energy Alternatives Planning (LEAP) (Mundaca, & Neij, 2009; Mondal, & Mezher, 2017). Such models are bottom-up, capable of evaluating the operation and investment of electricity supply technologies in the medium to long-term term (Hainoun et al., 2010). The MESSAGE modelling approach is a realistic assessment of the medium to the long-term choice of energy options for electricity generation under competitive conditions (IAEA, 2008; Hainoun et al., 2010). The least-cost determination in MESSAGE is through minimization of the total discounted energy system cost subject to the constraints representing demands, resource deficiency and capacity limits, which define the limits and constraints relation in the model (Kichonge et al., 2015).

The feasibility of a sustainable energy system can be analysed by applying energy, economic and environmental related models. Such models are used to help in the

planning of energy and the assessment of alternative energy policies and the integration of clean technologies in the long-run. (Mondal, & Mezher, 2017). Energy security however has implications of environmental concerns, liberalisation and deregulation and the growing dominance of market forces. These factors brought about the elements in energy security that affect the vital role of governments to supply electricity to meet growing demands at the optimal level (Khatib et al., 2000). In the past, and especially since the early 1970s, electricity security has been narrowly viewed as reduced dependence on oil consumption and imports, particularly in Organisation of Economic Corporation and Development (OECD) and other major oil-importing countries. Changes in oil and other energy markets have however altered the above view (Khatib, et al., 2000).

The empirical evidence on the nexus between long-term electricity supply or demand and the environment or GDP (Adom, 2011; Ogundipe & Apata, 2013), has become evidence of support to the planning and energy-related modelling in contemporary times. In addition, several empirical pieces of evidence confirm the relationship between electricity supply or use and economic growth or output (Adom, 2011; Qazi et al., 2012; Castellano, at al., 2015; Ramakrishna & Rena, 2013; Ogundipe & Apata, 2013). This explains why the largest economies of the world like US, China, Japan with massive economic outputs use enormous amounts of electricity much more than smaller economies of developing countries (Asif, & Muneer, 2007). Electricity and economic development interactions are seen from the nexus between GDP and electricity consumption per capita (Bergasse et al., 2013).

The focus of this thesis is however on the modelling of the available energy resources of Ghana needed to supply electricity in the long-term within a sustainable socio-economic development framework. The substantial gap between Ghana's electricity demand and supply has been the major cause of the country's electric power crises (Adom 2016; Eshun, & Amoako-Tuffour, 2016). Long-term projected electricity supply growth assumptions have profound economic, financial, social and environmental implications for national policy developments (Toth, 2012; Nkonoki & Sorensen, 1984). Ghana as a developing nation has always aspired to advance living standards. This can, however, be satisfied only through the sustained development of power markets as part of elementary infrastructure planning and development (Energy Commission, Ghana. 2018). The increasing interest in long-term energy planning for periods not less than 30 years is enormous in developed countries (Gustavsson, et al., 2011; Asif & Muneer, 2007; Morrison, et al., 2014). Countries, such as Japan, Sweden, South Korea, America and Australia, have short to medium term (5, 10 and 15 years) electricity generation plans that successively fit into the long-term (not less than 50 years) electricity development plan. Long-term plans in the electricity sector are key factors to the socioeconomic development of such nations (Australian Academy of Science, 2016; Tom Reed, 2015; Gustavsson et al., 2011). Modern energy services are key for the alleviation of poverty and boosting common growth and prosperity for developing nations. Access therefore to long-term electricity planning opens many new opportunities and aids efforts to affordable and clean energy services. Economic growth and human development become less of a challenge with access to clean energy and electricity. This supports the implementation of the United Nations Millennium Development Goals (MDGs) (IAEA, 2008; The WORLD

BANK, 2017). The fortunes of developmental activities are mostly the results of long-term planning and successful implementation of the plans in the electricity sector. The strive to build reliable electricity production system based on prudent, successful and all-inclusive national planning is an addition to the challenge of current and future power supply in a low carbon environment (Chu & Majumdar, 2012). Ghana lacks clear targets for long-term electricity supply and the reduction of carbon emissions resulting from electricity generation (Mandelli et al. 2014).

3.2.1 Electricity Power Supply Situation and Economic Growth in Ghana

Energy options for electricity generation in Ghana has been plagued with supply challenges with a reasonable impact on the Ghanaian economy (Kumi, 2017). Despite the developments in Ghana's electricity sector, the country suffered huge economic losses due to erratic power supply "dum-sor" challenges from 2006 through to 2015 (Adjaye, & Theo-Acheampong, 2015; Cobbinah, & Adams, 2018). Inadequate power supply and disruptions were estimated to vary yearly from 1% to 5% of Ghana's Gross Domestic Products (GDP) (Miketa, & Merven, 2013; Ouedraogo, 2017; Kumi, 2017).

On the average, Ghana in 2015 is said to have lost close to US \$2.1 million on the production of goods and services daily resulting from the country's severe electricity challenges (Kumi, 2017). In addition, as graded by the World Bank, Ghana's electricity challenge was seen as the second most important limitation to business activities in the country, liable to about 1.8% of GDP during the 2007 and 2010 power crisis (Mathrani, Santley, Hosier, Bertholet, Braud, Dawson-Amoah, & Reinoso, 2013).

Kumi, (2017) further confirmed the study by Ackah, (2015). Ackah (2015), estimated that Ghana on the average, lost production of goods and services worth US \$2.1 million per day (or, US \$55.8 million per month), due to power challenges alone. Issues of the inadequate power supply and “dum-sor” infringed heavily on the Ghanaian economy in 2015 (Adjaye & Theo-Acheampong, 2015; Clerici, et al., 2016; Cobbinah & Adams, 2018). The indication is that Ghana lost close to US \$680 million (2% of GDP) in 2014 due to the power crisis (Kumi, 2017). The power crises led to a decline in Ghana’s real GDP growth rate from 7.3% in 2013 to 4.2% in 2014 (Ackah, 2015). The decrease in the growth rate was mainly attributed to the challenges in energy resources needed for electricity generation, and partly due to the failure of long-term and successive implementation of electricity power planning studies, thereby reducing economic activities in Ghana (Adjaye & Theo-Acheampong. 2015). Issues of implementation of the planned installation of power plants to deliver electricity for consumption comes to play in the midst of Ghana’s energy crises.

3.2.2 Energy Resource Planning for Electricity Generation

Ghana has suffered from some major limitations to electricity supply. These limitations include but not limited to inefficient pricing, rising fuel cost, higher system losses, and climate change (Adom, 2016; Kwakwa, P. A., 2018). In the study, Adom (2016) recommended the adaptation of marginal cost pricing rule and reducing distributional losses below 5% to significantly aid the improvement of electricity supply security in Ghana. Basiago (1998), however, argues that a development strategy at the expense of long-term electricity planning,

environmental quality and social well-being cannot in the long-term be regarded as sustainable. In addition, achieving sustained economic growth will help boost supply security as well as investing in renewable and clean energies technologies for electricity generation (Basiago, 1998; Ministry of Energy, 2010; Adom, 2016; Ackah, 2016). These empirical findings, therefore, confirm the downward trend suffered by the electric power supply industry.

It has also been widely argued that, even though electricity use promotes socio-economic development, it can be associated with adverse environmental and social impacts (Schmalensee, R., 2012; Nachmany, M., et al., 2015). The persistent scarcity of energy resources and security of electric power supply gave birth to long-term planning and modifications in the electricity sector. Ghana's endowment with energy resources that can be exploited to meet its electricity requirement is enormous (Awopone, Zobaa, & Banuenumah, 2017). Concerns about the electric power industry to Ghana and the West African economies, in general, points out that, the level of electrification will hit 70 to 80% by 2040 in the midst of optimal power supply challenges and access for electricity consumption (Castellano et al., 2015). Ghana's current power shortfall is particularly serious for the reason that climate change is projected to increase the risk of drought over much of Africa in the 21st century (Urama & Ozor, 2010). The heavy dependence on hydropower resource has resulted in insecurity in electricity supply in Ghana due to periodic droughts (Dzobo, & Ennison, 2013). The increase in electric power demand (Aryeetey, 2005) and the low capacity utilization of the hydropower system due to perennial droughts (Dzobo, & Ennison, 2013) resulted in the difficulty of Ghana's main power supplier, Volta River Authority (VRA) to supply electricity during

years of low rainfall (Aryeetey, 2005). In addressing the shortfall in Ghana's energy demand, some thermal power systems that run on Natural Gas resource have been introduced into the electricity generation mix in the late 1990s (Aryeetey, 2005; Dzobo, & Ennison, 2013). In addition, the Public-Private Partnership (PPP) agreements in Ghana have been made to complement the hydropower and early thermal supply (Ministry of Finance and Economic Planning, 2011; AB & David, 2013). However, there are still challenges associated with their use that include the availability of fuel such as natural gas and generation cost (Dzobo, & Ennison, 2013).

It has been debated that the design of appropriate long-term strategies that would enable the establishment of high-quality electricity supply services is considered to be a manifestation of the poor energy and electricity policy targets in Ghana (Khatib, et al., 2000; Omer, 2008; Bazilian, et al., 2012). In addition, there exist seemingly disjointed carbon dioxide policies in relation to the implementation of energy planning and power supply in Ghana. The country's focus on electricity supply has been without key attention to carbon dioxide and other related emissions. Should the attention be on the usual strategy of Business as Usual (BaU) to tackle climate change mitigation, the country may never attain its climate change mitigation action (United Nations Economic Commission for Africa (UNECA), 2018). The country's national development strategy should therefore encompass a sustainable long-term electricity planning and environmental quality and social well-being with common economic benefits (Basiago, 1998; UN-DESA, 2013). Energy system models have become essential in the present day as a result of the key importance they play in policy decision making (Messner, 1997).

Kemausuor et al. (2011) argued that Ghana government over the years made high provisions for energy services on the country's development agenda. However, past and existing energy and electricity policies have not delivered effective results to quicken the efficient supply of electricity at the optimal level to areas where the services are highly needed. They pointed out that the choice of future energy paths and policies will impact significantly on Ghana's energy and electricity security amidst uncertain impending changes and implication). Evidence from the variance decomposition made by Kemausuor, et al (2015), shows that future shocks of 21 % of carbon dioxide emissions will be borne from fluctuations in energy use, as against 8 % and 6 % for GDP and population, respectively. They further showed evidence of unidirectional causalities running from carbon dioxide emissions to energy use, carbon dioxide emissions to GDP and carbon dioxide emissions to the population. The study recommended renewable energy and clean energy technologies into Ghana's energy mix to help mitigate climate change impact in future (Asumadu-Sarkodie, & Owusu, 2017). In addition, Kemausuor et al (2011), in a review paper appeals for consistent national energy policy with inputs from a wider consultation that has precise targets and laid down strategies.

A number of studies have been done in Ghana that has applied optimisation models for long-term energy planning. However, studies on the optimal generation pathways and the development of selected generating technologies for power generation in the long-term is not enough to some extent. The main objective of energy supply options for electric power supply system is to ensure an adequate and continuous provision of electricity with a suitable degree of security and

quality (Aryeetey, 2005). The concept of energy modelling has become an important instrument for energy and environmental impact of policy studies (Kavrakoğlu, 1987; Messner, 1997). Important energy modelling tools have been in existence since the unexpected worldwide energy crisis (Messner, 1997; Hogan, 2002). The preliminary stages of the development of energy modelling for policy analysis brought about the interactions among problem identification for the model formulation, problem analysis, and policy implementation in economics and operations research for many nations (Hogan, 2002). It has been found that higher consumption of fossil fuels for electricity generation leads to the increase in greenhouse gas emissions, particularly carbon dioxide (CO₂) that contribute to global warming (OECD & IEA, 2011). It could be argued that Ghana's sustainable energy and electricity future will require a transformation in the manner electricity is generated for final demand. Green growth must play a key role in an effort to provide access to modern energy services, protect the global environment and ensure reliable energy supplies (OECD & IEA, 2011).

3.2.3 Energy, Economic and Environmental (3Es) Related Systems Modelling

Not only has the world focused attention on the high cost of fuels for electricity production but also the resulting impacts of power plants that use the fuel. Results of computer-based energy, economic and environmental models provide the optimization of the analysis that has become a major recommendation to policymaking in the advancement of the introduction of new energy strategies that may control carbon footprints (Fairuz, et al., 2013). Macroeconomic models that include general equilibrium and neoclassical growth models were developed to account for energy as a factor input of an economy (Weyant 1981). Sector-wide

impacts of sustainable energy policies can be assessed by linking an economic model with the energy-environment model and the integrated energy-economy model will confirm the transformation of economic sustainability (Mondal, & Mezher, 2017). Optimisation models in general attempt to find least-cost solutions of technology choices for energy systems based on various policies and market constraints (Mundaca & Neij, 2009; Kichonge, et al., 2015; Supekar, & Skerlos, 2017). Least-cost models are usually aimed at minimizing the total cost of energy to achieve a certain optimal power supply and emission target using electricity supply technologies (Supekar, & Skerlos, 2017). Optimization models were projected and developed to support electricity systems planning and the management of Green House Gasses (GHG) emissions mitigation particularly through the adoption of renewable and clean energies (Liu, Tzeng, & Hsieh, 1992; Xiao, et al. 2009). Optimization is considered as an effective tool for identifying optimal strategies within complex management systems (Wiig, 2000). This calls for the application of optimization models with the implementation of the results to relatively increase electricity production to meet the demand of rising share of electricity consumption (Energy Commission, Ghana, 2018; Theo-Acheampong & Ankrah, 2014).

By simulating conventional and non-conventional energy technologies, the economic and environmental implications of renewable energy policy was conducted for Ghana (Awopone et al., 2017). The study's methodology applied the Open Source Energy Modelling System (OSeMOSYS), an optimisation model for long term energy planning. To also develop the optimal generation pathways and dispatch scheduling of selected generating technologies for power generation in

Ghana, Awopone et al. (2017) integrated the OSeMOSYS in the LEAP model. The alternative least cost generation options for electricity supply system revealed that suitable policies for clean power generation have an important role in Ghana's CO₂ mitigation (Awopone et al., 2017). The modelling and sensitivity analysis applied in the study indicated that measures of wide range implementation of energy efficiency are needed for renewable energy technologies to contribute more than 70% of Ghana's needed electricity generation by 2040. As a result, the benefit of significant economic and environmental sustainability of the energy and electricity sector could be achieved (Awopone et al., 2017).

A study was conducted by Hainoun, Aldin, & Almoustaf (2010) to assess electricity security supply for Syria based on the minimization of the total system cost of electricity for a period of 2003 to 2030. By use of the MESSAGE model, an optimal long-term energy supply strategy was formulated based on the minimisation of the total system costs method for the entire study period 2003-2030. The methodology for the study also included the modelling of the national energy chain that covered all energy levels and conversion technologies. The findings showed that Syria's energy system is certain to rely on oil and gas for electricity generation. This revelation identifies the challenge for the future economy of Syria if stringent policies are not put in place for the expected long-term electricity sector.

Optimal modelling tools that attempt to find least-cost solutions of technology choices for energy systems (Mundaca & Neij, 2009), is normally joined with general equilibrium models, such as MESSAGE-MACRO (Messner and

Schrattenholzer, 2000). With the help of these models, the global impacts of policies that internalize the external cost of electricity generation using a combined energy system and macroeconomic model (Klaassen & Riahi 2007) (MESSAGE-MACRO) were made. Specifically, the impacts on energy use and the resulting costs of electricity generation and GDP-losses were assessed (Klaassen & Riahi, 2007).

Klaassen & Riahi (2007) conducted a study of optimization on the use of MACRO cost information for electricity demand category made on the internalisation of the externalities. The study used a combined energy systems and macroeconomic model (MESSAGE-MACRO) to examine the global impacts of the external costs related to air pollution damage of electricity generation. Results of the study show that clean and advanced technologies increase their share in global electricity production, lowering global carbon dioxide emissions by 3% to 5%, between 0.6% and 1.1% gross domestic product losses. The GDP values were comparatively high during the initial phase of the policy initiation, pointing to the need for a gradual phasing of such policies (Klaassen, & Riahi, 2007).

Carbon dioxide is a foremost GHG contributor to threatening global warming (AlFarra, & Abu-Hijleh, 2012). A study by Kichonge, et al., (2015) applied MESSAGE to explore energy supply options in meeting Tanzania's electricity demands projections. The study applied the methodology of developing economic scenarios that included a dry weather scenario to explore how the country's electricity system would behave under dry weather conditions. The study revealed the implications of capital investment costs versus environmental impacts

concerns. Results of the study revealed that projected final electricity demand as expected will require the total installed capacity to further increase from a base value of 804.2 MW at a 9.05% and 9.8% of business as usual and high economic scenarios, respectively. The least-cost modelling results concluded that meeting final electricity demands without considerations of environmental impacts concerns is cheaper. However, they noted that a development strategy that solely emphasizes economic benefits at the expense of long-term electricity planning, environmental quality and social well-being cannot in the long-term be regarded as sustainable (Basiago, 1998; UN-DESA, 2013).

In addition, keeping with the Kyoto Protocol leads to the decision of the integration of the energy mix into electricity schemes to mitigate CO₂ emissions. AlFarra & Abu-Hijleh (2012) used the optimal generation model, MESSAGE to evaluate the effectiveness of the United Arab Emirates (UAE's) proposed nuclear energy strategy in mitigating CO₂ emissions from the built environment up to the year 2050. Based on the set scenarios, nuclear energy was found to be a more practical option in mitigating CO₂ emissions. They also demonstrated economic viability for the UAE.

Furthermore, research conducted by Morrison et al (2014) for California used an inter-model comparison of nine California state-wide energy models on the ranges of GHG mitigation scenarios and future modelling needs. The diversification of the model's results found that annual state-wide GHG emissions are 8-46% lower than 1990 levels by 2030 and 59-84% by 2050. The importance of energy modelling on a large scale built on the fundamentals of research in energy, economics and

environment (Hogan, 2002) helps in policy decision making for the integration of modern energy systems and development (Rakshit et al., 2018).

3.3 Summary

The Chapter provides a review of Electricity Supply Optimality for Long-Term Generation as well as the Power Supply Situation and Economic Growth in Ghana. In addition, a literature review on energy resource planning for electricity generation with emission concerns was presented. The chapter also presented the energy, economic and environmental related systems modelling that provided key insights into energy optimization modelling systems.

CHAPTER FOUR

METHODOLOGY

4.1 Introduction

This chapter discusses the methodology employed in the study. It presents the optimization procedures used to achieve the objective of the study. The first section of the chapter covers the description of the “Model for Energy Supply Strategy and their General Environmental Impacts” (MESSAGE) modelling processes that have been employed and the empirical model specification. The second section details the structure and sources of data, including the electricity demand projections that have been employed in the study. The last section presents the modelling framework and the basic assumptions that have been employed in the study.

4.2 The Outline of the MESSAGE Model

MESSAGE is a software designed for modelling energy systems (i.e. energy supplies and utilization) for optimization. MESSAGE was developed at the International Institute for Applied Systems Analysis (IIASA). The underlying principle is to optimise an objective function under a set of constraints that define the possible region containing all potential solutions of the problem (Messner, 1997; IAEA, 2007; Borba, B. S. M., Szklo, A., & Schaeffer, R., 2012).

The objective function of the study seeks to assess current and future energy supply potentials of indigenous energy resources and the importation of fuel options for the evaluation of long-term electricity supply. The objective function aids the choice of the solution considered best, according to the specified criteria of the Ghanaian energy system for electricity generation. In general, the MESSAGE

model belongs to the class of mixed integer programming models as they contain some integer variables (Messner, 1997; IAEA, 2007). In addition, the MESSAGE model can be used to develop to model another non-energy system. However, the main objective of developing the MESSAGE software was to facilitate the building of an energy system model (IAEA, 2007; Nakata T., 2004). The software is designed to formulate and evaluate alternative energy supply strategies in line with user-defined constraints such as limits on new investment, fuel availability and trade, environmental regulations and market penetration rates for new technologies (IAEA, 2007). The MESSAGE model is structured from the general data to the resources available to a nation, such as Ghana for power generation.

4.2.1 MESSAGE Model Structure

The structure of the MESSAGE model is as follows:

General: The window has been designed for entering and editing of general data or some main features of the selected case study that include the time horizon, discount rate and country name.

Load regions: This portion allows for the definition of seasons in the country, day types in each season and periods of variations in the energy demand for each day type.

Energy Forms: Allows the modelling of various energy levels in an energy system starting from energy resources to useful energy forms for consumption.

Demands: Demand is an exogenous data requirement in this study and for the model. Data for the final demand of each year during the study period is presented in the demand portion.

Constraints: The constraints part allows the setting of boundaries or limits on the use of resources, energy forms and the various technologies defined in the energy system.

Technologies: This portion defines the various conversion pathways from one energy form to the other in an energy system. For instance, the technology ‘Gas Thermal Power Plant (GT_PP), converts primary gas to secondary electricity.

Storages: This window allows the modelling of reservoirs for hydropower plants.

Resources: For every nation, there may exist a natural resource for electricity generation. For Ghana as a country, natural gas is a resource. The resource portion allows user-defined natural resources and the available quantum in a country.

The MESSAGE software consists of the following components:

A user-interface for building a model for a nation or region.

Databases, such as application database.

A matrix generation program called “mxg”.

An optimization program called “opts”.

A program for the post-processing of the solution for extraction of results called “cap”.

MESSAGE is used to model the power supply sector of Ghana by means of the principle of the reference energy system (RES). The RES permits the representation of the entire energy network of Ghana, including possible development paths (Rečka, 2011; Selvakkumaran & Limmeechokchai, 2011). RES, as represented in Figure 4.3 is composed of energy resources and sources, energy carriers, otherwise known as forms and technologies. RES is a network flow

of energy carrier from one process to the other starting from the resource to the final consumer.

Energy forms include each level of energy chains, technologies using or producing these energy forms, and the energy resources. MESSAGE defines energy forms and technologies in all steps of energy chains, that includes identification of energy chain levels beginning from the demand for the resources, the energy forms to final energy services. MESSAGE computes energy demand from the first level of each energy chain up to the energy resource level. Final demand level is distributed according to the types of energy consumption (Van Beeck, 1999; Pinthong & Wongsapai, 2009).

Substantial electricity supply in Ghana is expected to alleviate the current deficit in demand which is key to Ghana's socio-economic development.

The MESSAGE model is relevant to this study because of the wide usage it has for the formulation and evaluation of alternative energy supply strategies in line with user-defined constraints.

The model, in addition, has an inclusion of an optional number of primary energy resource categories allowing for the modelling of the nonlinear relation between extraction costs and available amount of a resource; the explicit consideration of demand load curves, in order to take account of e.g., the variation of demand for electricity; the calculation of residual discharges to the environment; increased program flexibility allowing e.g., for easy modular inclusion and removal of technologies (IAEA, 2007).

The study focused on the analysis of Ghana's electricity supply system based on the projected electricity demand of the country by Sarkodie (2017). An alternative scenario and pathways for electricity supply system in Ghana have been developed for the period ending in 2047. The Schematic diagram of the MESSAGE model is presented in Figure 4.1. The diagram presents a generic input and output of the MESSAGE model.

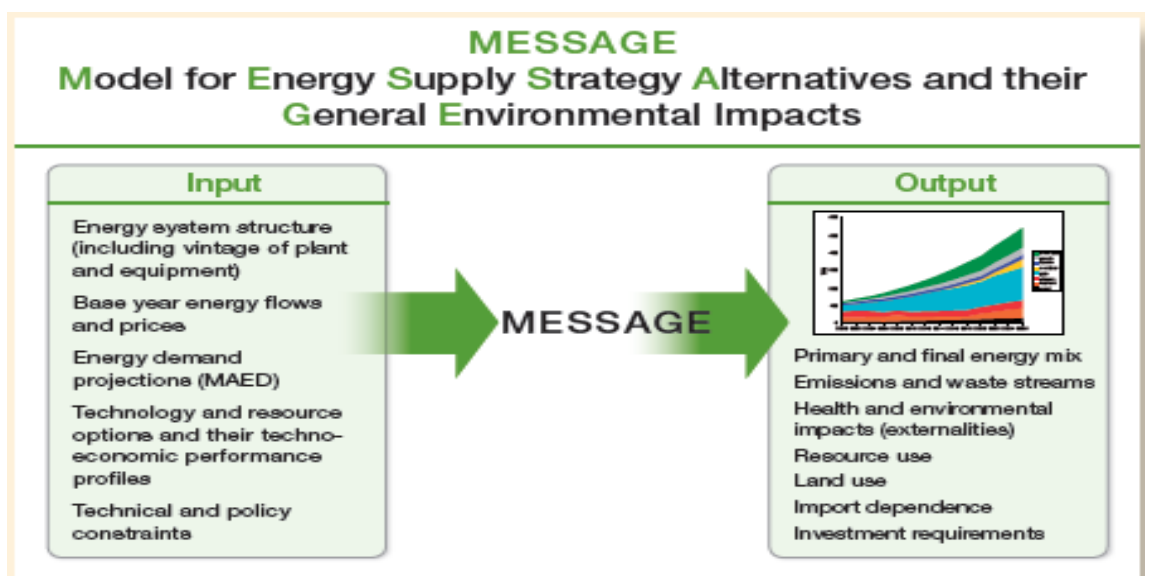


Figure 4.1: Schematic diagram of the MESSAGE model

Adapted from IAEA User's Guide for MESSAGE

4.2.2 Development of Scenarios

Scenarios provide a framework for exploring future energy perspectives, including various combinations of technology options and their implications. Scenarios are useful tools for investigating alternative future developments and their implications for learning about the behaviour of Ghana's complex energy systems. Two economic scenarios, namely; business as usual (BAU) and high economic growth scenario (HEG), has been developed.

Business-as-usual Scenario (BAU)

This scenario is characterized by the most likely path of development in the absence of any major intervention in Ghana's electricity sector. This scenario incorporates existing government plans and policies based on the electricity demand projections made by Sarkodie (2017). In this scenario, all existing and committed power plants were considered, including the deployment of clean technologies per the existing trends and proposed projects for renewables and nuclear.

High Economic Growth Scenario (HEG)

The HEG scenario is based on estimates of electricity demand within the period set for the BAU scenario. The electricity demand projection for the HEG scenario was computed to be 10% more than the BAU scenario. All other assumptions with respect to technologies and other parameters are similar to that of the business-as-usual scenario.

4.2.3 Empirical model

The principle of the MESSAGE model employed in this study is the optimization of an objective function under a set of constraints that define the feasible region containing all possible solutions to a problem. Mathematical techniques tied up with the model comprises of linear and mixed-integer programming. The purpose of linear programming (LP) applications is that all the limits and the objective function (optimization target) are linear functions of the decision variables. The Mixed-integer used in the model is due to integer values at the optimal solution requirements by some of the decision variables. The energy optimization model is a dynamic linear programming model of the overall energy system. The objective

function generally applied is to minimize the sum of the discounted costs, or the net present value, of Ghana's overall electricity system. The objective function used in the minimization process in MESSAGE modelling approach is as shown in equation 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 cost,

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 installations of technologies

i_{jt} : Specific investment

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

The model computes the objective function in equation 1 to satisfy a set of constraints that have been set to satisfy the aim of minimization of the net present value.

The investment costs of a technology (power plant) in the model are considered as dependent variable required as per kW specific values. These

costs are multiplied by the annual new installations of technologies to yield the overall cost of investment. The investment costs of a technology are commonly expressed as:

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

(2)

As represented in the objective function, 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 the power plants on a yearly basis for the measurement of 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 in equation 1 below:

$$C_{am} = CRF (i, R_{proj}) \cdot C_{NPC} \quad (1)$$

where:

C_{NPC} = the net present cost [\$]

i = the annual real discount rate [%]

$R_{proj/plant}$ = the project or plant lifetime [yr]

$CRF ()$ = a function returning the capital recovery factor

The constraints with the modelling processes are discussed in the equations below.

Equation 3, is the electricity demand-supply balance constraint to the objective function. At the optimal level, the supply of electricity must at least meet the demand.

$$\sum_{j \in P_e} \eta_{jt} X_{jt} \geq \sum_{j \in C_e} X_{jt} + D_{et}$$

(3)

where

P_e : producers of energy carrier

C_e : energy consumers

D_{et} : demand for, which is exogenous

η_{jt} : Conversion efficiencies of energy technologies

The illustration ensures that all producers of energy carrier (technologies in P_e) supply sufficient electricity for either all consumers (technologies in C_e) or for the exogenous demand for e (D_{et}), taking into account the conversion efficiencies of the technologies, (η_{jt}).

As shown in equation 4, the capacity requirements of energy technologies are determined by a vintage type of approach. The production in a period is related to all capacities up to a certain age of a power plant (the technical plant life, Π_j), including the contribution of capacities existing before the first modelled year (h_{jt}).

This illustrates a major constraint to electricity production:

$$n_{jt}X_{jt} \leq \alpha_{jt} \sum_{\tau=t-\Pi_j}^t \Delta_{\tau}Y_{\tau j} + h_{jt}.$$

(4)

Where

n_{jt} : Conversion efficiencies of energy technologies

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

α_{jt} : the plant factor

Π_j : the technical plant life,

Δ_t : Length of period t in years

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

h_{jt} : the first modelled year

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

Equation 5, is the constraint on the overall resource consumption controlled by the quantities extracted over the entire model horizon to the available quantities of resources (R_j):

$$\sum_{t=1}^t \Delta_{\tau}X_{jt} \leq R_j.$$

(5)

Where

Δ_t : Length of period t in years

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

R_j : available quantities of resources

Additional constraints on resource extraction, such as depletion constraints limiting the quantity extracted during a period to the volume still available, or constraints on the growth of extracted quantities, can also be formulated.

The introduction of emission constraints or limits on the application of certain electric power supply technologies (power plants) has been very key to the modelling processes of this work. The environmental aspects were analysed by accounting and limiting the amounts of pollutants (CO₂ emissions) emitted by the technologies at various steps in electricity supplies (IAEA, 2007; Rao et al., 2008). The accounting and limiting of the amounts of pollutants aided the evaluation of the impact of environmental regulations on energy system development (IAEA, 2016), in Ghana, in addition to the economic results derived

4.3 Data Source and Structure

4.3.1 Source of Data

The study used data on 45 energy technologies or power plants. The type of data used in the study is secondary. The data on the technologies include resource extraction, fuel imports, conversion technologies, transmission and distribution to the provision of electricity end-use services such as lighting, space conditioning, industrial production processes, among others.

The modelling period is a 30-year, spanning the period 2018 to 2047. Technical and economic input data for the power plants are found in Tables 4.1 to 4.3. Hydropower plants were renamed as “H”, thermal as “TH” and solar as “S”. Committed power plants have also been named as “CP”. Data for the study were acquired from state institutions responsible for energy planning and ownership of power plants in Ghana and other international body or institution include the International Energy Agency (IEA). Table 4.1 shows the data on the existing technologies or power plants in the country for the study. Table 4.2 and Table 4.3 represents the data on future technologies that include committed and possible power plants, respectively. The technical parameters consist of the capacity of the plants in megawatts, the lifespan, plant factor, efficiency and the type of fuel used. The economic characteristics are made up of the investment cost of power plants, fixed and variable operation and maintenance (O&M) cost. For the existing power plants, the date in which the technology came online has been outlined while the committed or possible date has been shown for future technologies.

Generally, input data required for the Electricity Assessment Study conducted using the MESSAGE modelling framework was depended on the study scope and objectives. The data requirements for the electricity system assessment study is characterized into:

Structure of the energy system

Energy system development options

Other data – according to the study's scope and objectives

Important inputs or data for the model were harmonized set of technical, economic and environmental parameters. The structure of the data requirement of the study

is presented in the next section and the technical and economic parameters of existing, committed and possible conversion technologies in Ghana are presented in Tables 4.1 to 4.3.

4.3.2 Structure of Data

The Ghana power system study, in this case, comprises all energy forms or utilisation. The study is typically used for the analysis and assessment of Ghana's electricity development strategies and plans. A detailed elaboration of the structure of data for the modelling framework is presented in the subsequent sections.

4.3.2.1 Structure of the Energy System

Resources

Resources are exhaustible materials available for energy use. They include but not limited to gas, oil, wood, coal and uranium. Available volume or equivalent available energy quantity of all resources irrespective of their current usage status or quality is required. The energy resources considered in this study for Ghana's electricity generation is natural gas exploitation and biomass.

Sources

Sources of energy show the origin of the energy that is used to generate electricity. For instance, renewable energy sources for electricity generation include hydro, wind, solar, geothermal, biomass, among others. Those sources are not exhaustible and are approached differently in energy models (US Energy Information Administration (EIA), 2018). It is important to provide the expected (or average) annual availability and seasonality (i.e. changes in the quantity of energy available during a year) for these sources of energy.

Energy Conversion Technologies

List of existing technologies used in energy conversion processes that were used include extraction technologies (natural gas or coal extraction or fuel enrichment), transformation technologies (power plants, refineries and LNG plants) and transmission/transport/distribution technologies (electricity transmission network, oil pipelines, LNG ships).

For the purpose of this study, the electricity conversion technologies considered include hydro, solar PV, solar thermal, biomass, wind, conventional gas turbine (GT), heavy fuel oil (HFO), light crude oil (LCO) combined cycle gas turbine (CCGT) power plants, coal-fired power plant and nuclear power plant.

The list of technologies and level of details depend on the study scope and objectives. Usually, a certain level of aggregation/approximation is applied to make data set applicable to the study needs. Each energy or electricity technology can be characterised by its:

Technical Characteristics:

Inputs (crude oil, natural gas, nuclear fuel, electricity)

Outputs (electricity, heat)

Conversion characteristics (heat rate, efficiency, losses)

The capacity of conversion (installed power, refining capacity) and

Other technical aspects (security of supply requirements – system reserve, forced outage rates, maintenance, refuelling periods, lifetime, and degradation of technical characteristics during lifetime, rehabilitation plans and improvements and must run plants)

Environmental Characteristics: includes various environmental impacts of power plants that include: by-products of energy conversion – emission to air,

water; land use, water use) and systems in place to control environmental pollution, such as flue gas desulphurisation, DeNO_x systems, wet/dry cooling.

Economic Characteristics: the costs related to the development and operation of the technologies can be grouped into:

Fuel costs – costs of fuels used as inputs into a technology

Variable costs – costs related to a technology output (these costs exist when technology is producing/generating its output)

Fixed costs – costs related to a technology capacity, that is to the capability of a technology to produce output (these costs exist even when technology is not producing/generating its output)

Investment costs: this is specific to existing technologies, that is, technologies already in operation at the beginning of the planning horizon. Investment costs are not important if the equipment is already in place. However, when existing technology is considered for future expansion appropriate investment costs should be provided. The same is applicable when technology is considered for rehabilitation (appropriate investment costs and changes in other operational costs have to be specified).

4.3.3 Electricity Demand Projections

The final electricity demand projections for the study is taken from the work of Sarkodie (2017), electricity demand projections. By the use of an Autoregressive Integrated Moving Average (ARIMA) model, Sarkodie (2017), forecasted Ghana's electricity consumption by the year 2030. The forecast by Sarkodie (2017) was based on a time series data that spans from 1980 to 2013. It was predicted that

Ghana's electricity demand will grow from 8.52 billion kWh in 2012 to 9.56 billion kWh in 2030. The demand projections are represented in Figure 4.2.

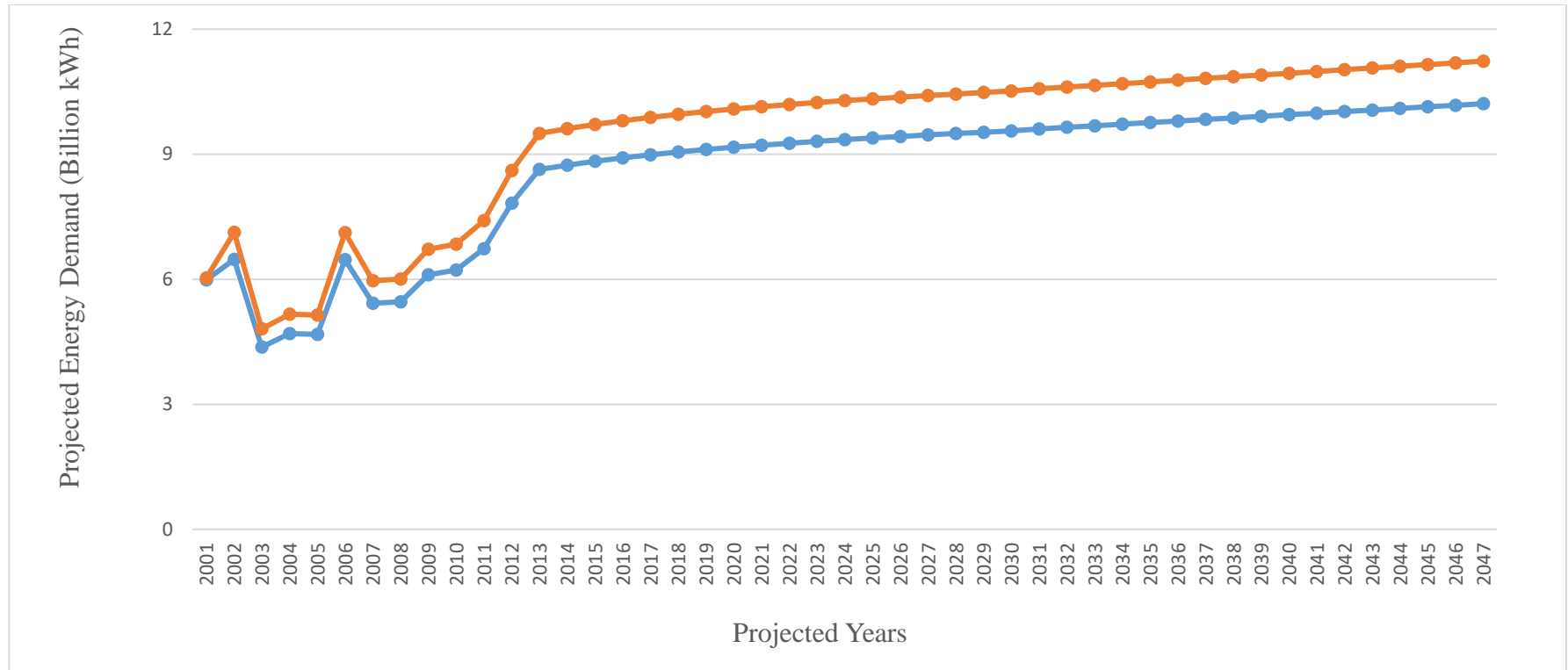


Figure 4.2. Projected BAU and HEG Scenario Energy Demand

Source: Sarkodie, 2017

Table 4.1: Technical and economic characteristics of existing conversion technologies

| Existing Conversion Technologies | | Size/Capacity (MW) | Investment cost (US\$/kW) | Variable O&M cost (US/MWh) | Fixed costs (US\$/kW/yr) | Online Date (Year) | Plant life (years) | Plant Factor (share) | Plant Efficiency (%) | Input (Fuel type) |
|----------------------------------|------|--------------------|---------------------------|----------------------------|--------------------------|--------------------|--------------------|----------------------|----------------------|-------------------|
| Hydro | H1 | 900 | | 0.98 | 9.16 | 1965 | 50 | 51 | 100.0 | Water |
| | H2 | 140 | 200.0 | 0.98 | 9.16 | 1982 | 50 | 65 | 100.0 | Water |
| | H3 | 340 | 1818.7 | 1.63 | 27.74 | 2013 | 50 | 23 | 100.0 | Water |
| Thermal | TH1 | 230 | 2217.4 | 5.0 | 14.54 | 2016 | 25 | 85 | 33.6 | Natural Gas (NG) |
| | TH2 | 180 | 1111.1 | 4.5 | 11.83 | 2010 | 30 | 85 | 36.6 | NG |
| | TH3 | 300 | | 2.0 | 17.00 | 1998 | 30 | 85 | 43.8 | NG/LCO |
| | TH4 | 200 | 870.0 | 3.5 | 12.30 | 2016 | 25 | 85 | 31.3 | NG |
| | TH5 | 320 | 2727.3 | 4.9 | 30.94 | 2000 | 25 | 85 | 45.8 | NG |
| | TH6 | 100 | 717.0 | 6.5 | 14.30 | 2009 | 25 | 85 | 30.2 | NG |
| | TH7 | 45 | 1000.0 | 4.5 | 11.83 | 2010 | 20 | 85 | 35.1 | NG/LCO |
| | TH8 | 300 | 2647.0 | 3.5 | 16.00 | 2018 | 25 | 85 | 43.6 | NG/LCO |
| | TH9 | 100 | 714.0 | 4.5 | 11.83 | 2013 | 25 | 85 | 28.4 | LCO |
| | TH10 | 0 | 2827.1 | 3.5 | 177.83 | 2015 | 3 | 85 | 44.7 | HFO/NG |
| | TH11 | 450 | | 3.5 | 177.83 | 2018 | 10 | 85 | 44.7 | NG/HFO |

| | | | | | | | | | | |
|--------------|------|------|--------|-------|-------|------|----|----|-------|--------|
| | TH12 | 0 | | 4.5 | 12.38 | 2007 | 20 | 80 | 44.7 | NG/LCO |
| | TH13 | 25 | 750.0 | 5.5 | 34.00 | 2015 | 25 | 80 | 40.4 | NG/DFO |
| | TH14 | 33 | | 3.5 | 17.50 | 2016 | 20 | 85 | 34.4 | LPG |
| | TH15 | 250 | | 3.5 | 16.00 | 2017 | 25 | 85 | 40.1 | HFO/NG |
| | TH16 | 320 | | 3.5 | 16.00 | 2017 | 25 | 85 | 43.7 | NG/LCO |
| | TH17 | 49.9 | | 5.5 | 34.00 | 2018 | 4 | 85 | 40.4 | NG |
| | TH18 | 16.3 | | 5.5 | 34.00 | 2016 | 5 | 80 | 40.4 | DFO |
| | TH19 | 16.3 | | 5.5 | 34.00 | 2016 | 5 | 80 | 40.4 | DFO |
| | TH20 | 30 | | 3.5 | 17.50 | 2016 | 10 | 85 | 31.0 | LPG |
| | TH21 | 20 | | 3.5 | 17.50 | 2016 | 10 | 85 | 32.1 | LPG |
| | TH22 | 0.1 | | 4.2 | 35.00 | 2016 | 15 | 20 | 35 | MSW |
| Solar | S1 | 18 | 1500.0 | 201.8 | 0.00 | 2015 | 20 | 17 | 100.0 | Solar |
| | S2 | 1.8 | 3232.8 | 166.9 | 0.00 | 2013 | 15 | 17 | 100.0 | Solar |
| | S3 | 150 | 2750.0 | 0.0 | 20.00 | 2018 | 25 | 14 | 100.0 | Solar |

Table 4.2: Technical and economic characteristics of committed conversion technologies

| Committed Power Plants | PPs | Size/Capacity (MW) | Investment cost (US\$/kW) | Variable O&M cost (US/MWh) | Fixed costs (US\$/kW/yr) | Committed Date (Year) | Plant life (years) | Plant Factor (share) | Plant Efficiency (%) | Input (Fuel type) |
|------------------------|-----|--------------------|---------------------------|----------------------------|--------------------------|-----------------------|--------------------|----------------------|----------------------|-------------------|
| | CP1 | 180 | | 4.9 | 30.94 | 2019 | 25 | 85 | 41.6 | NG; LCO |
| | CP2 | 450 | 1041 | 3.5 | 16 | 2019 | 20 | 85 | 45.5 | LPG |
| | CP3 | 230 | | 4.17 | 14.54 | 2021 | | 85 | 33.6 | NG |
| | CP4 | 100 | | | | | | | | Tidal_Wave |
| | CP8 | 225 | 1437 | 9.5 | 33.9 | 2020 | 15 | 27 | 100 | Wind |

Table 4.3, Technical and economic characteristics of possible conversion technologies

| Possible Conversion Technologies | Size/Capacity (MW) | Investment cost (US\$/kW) | Variable O&M cost (US/MWh) | Fixed costs (US\$/kW/yr) | Possible Date (Year) | Plant life (years) | Plant Factor (share) | Plant Efficiency (%) | Input (Fuel type) |
|----------------------------------|--------------------|---------------------------|----------------------------|--------------------------|----------------------|--------------------|----------------------|----------------------|-------------------|
| Mini_Grid_System | 500 | | 0 | 10.3 | | 50 | | 100 | Water |
| Rooftop_Solar | 37.7 | 2750 | 0 | 10 | | 40 | | 100 | Sun |
| Wind_PP | 50 | 2313 | 0 | 30.3 | | 20 | | 100 | Wind |
| Biomass_PP | 110 | 3700 | 4.2 | 70 | | 45 | 70 | 32 | Biomass |
| Single_CG_PP | 1000 | 4500 | 18.13 | 12.48 | | 30 | 90 | 30 | NG |
| LNG_PP | 500 | 1500 | 18.13 | 14 | | 30 | 90 | 55 | Secondary_LNG |
| Gas_Thermal | 1000 | 700 | 18.33 | | | 30 | 90 | 35 | NG |
| CCG_Thermal | 500 | 1186 | 18.13 | 12.48 | | 30 | 85 | 55 | NG |
| Nuclear_PP | 1200 | 5000 | 4.29 | 90.02 | 2030 | 60 | 90 | 90 | Uranium |
| Coal_PP | 700 | 1900 | 52.56 | 50 | 2023 | 30 | 0.95 | 40 | Coal |

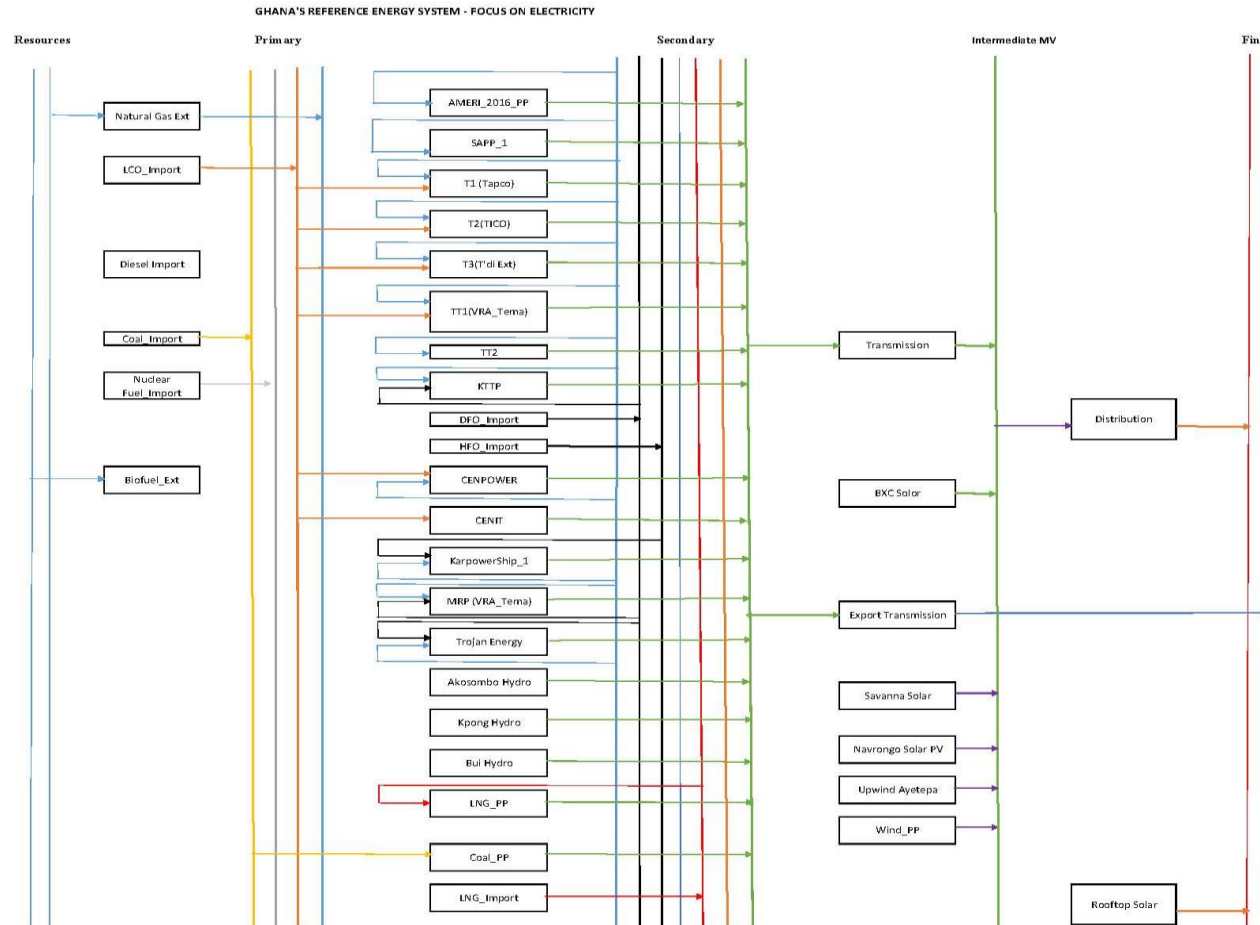
Source: International Energy Agency, 2015

4.4 Modelling framework and Basic Assumptions

4.4.1 Reference energy system (RES)

The RES proposed for Ghana power system accommodates resources, primary, secondary, intermediate medium voltage (mv) and final electricity demand levels. The schematic flow of the energy chains, levels and conversion technologies in the RES are presented in Figure 4.3. Rectangles in the RES represent the technologies, which contain the techno-economic data. The energy resource level is characterized by wood and natural gas, as locally available resources.

Energy carriers in the form of natural gas (NG), Coal, Liquefied Crude Oil (LCO), Biomass and Nuclear, define primary energy level in the energy chain. The secondary energy levels are burned out of the primary energy levels. They are composed of Heavy Fuel Oil (HFO), Diesel Fuel Oil (DFO), Liquefied Petroleum Gas (LPG) and Liquefied Natural Gas (LNG) that are combined with the primary levels to produce secondary electricity. Intermediary of primary and secondary energy levels are electricity conversion technologies whose main inputs are energy carriers from the primary energy level. Electricity transmission and distribution network connect secondary and final energy levels. The final electricity demand developed from the model's external factors is given at the first level of each energy chain. The model calculates the equivalent productions of each of the technologies at the succeeding levels of the chain up to the energy resource level, which then gives the optimal technical choice by minimizing the total system cost, while meeting the given final electricity demand. Figure 4.3, is a description of a simplified schematic flow of the energy chains, levels and conversion technologies in a reference energy system (RES), electricity RES for Ghana.



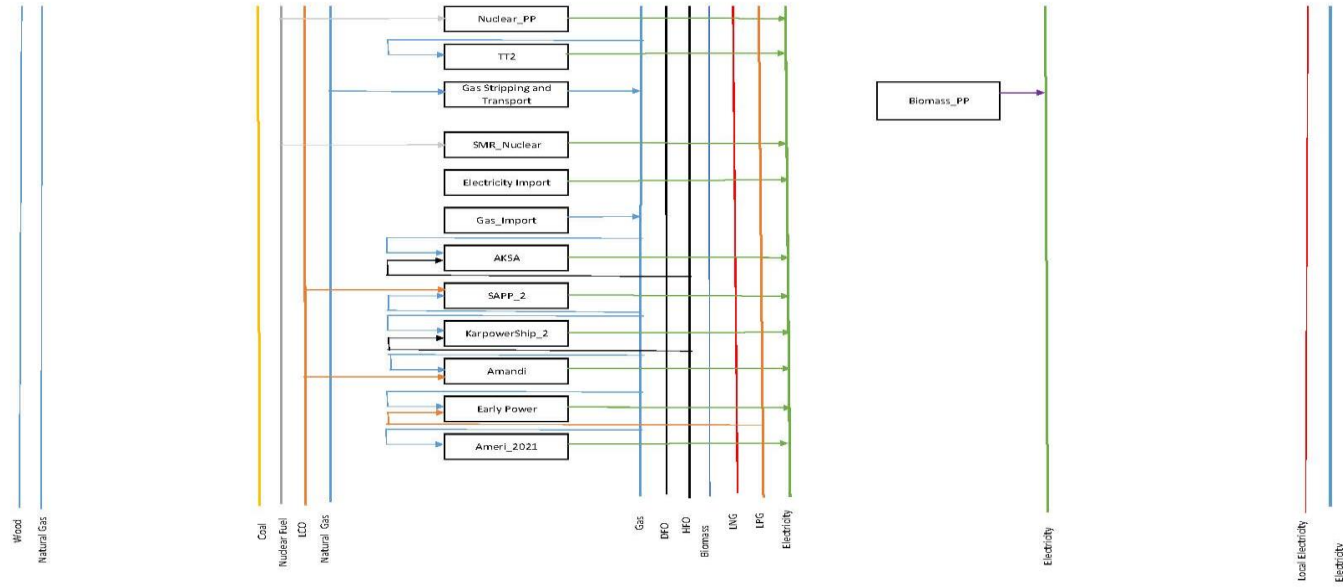


Figure. 4.3: Ghana' Electricity Reference Energy System (RES)

Source: Author's draft, 2018

4.4.2 Modelling basic assumptions

The general assumptions considered in modelling energy supply options for electricity generation in Ghana are as follows:

The model scenarios span from 2018 as the base year to 2047 as the last model year. A time step of one year has been adopted throughout the study period;

The operation time thus electricity output for solar PV, solar thermal and wind power plants follows the proposed seasonal and daily sunshine/wind variation;

The discount rate parameter for economic evaluation of the future investment project was set to 17% at the June 2018 Bank of Ghana Bill Rates in each scenario;

The entire national electricity system has been simplified and modelled as a single grid system;

Electricity imports were to remain at zero from the year 2018

All wind Power Plants were modelled to be on-shore power plants.

Total transmission and distribution losses were set at 23% for the World Bank 2014 report.

Potential hydro sites were to be modelled as one hydro plant known as Composite Hydro, however, due to inadequate data for modelling they were not considered.

4.5 Summary

The Chapter outlined the structure of the MESSAGE model, developed scenarios (BAU and HEG) and the empirical methodology used in the modelling. The empirical methodology included the setting up of an objective function for the model, subject to the constraints (electricity demand-supply balance, the capacity requirement of technologies and the resource composition) used in this research. In addition, the structure and sources of data, including the electricity demand

projections and the basic assumptions that have been employed in the study have been presented. The succeeding chapters (Chapter 5 and 6) will present the analysis and discussions of the output based on the least-cost energy supply options for electricity generation for the period 2018-2047. It will also present the concluding remarks for the entire study and recommendations for policy decisions and future research.

CHAPTER FIVE

ANALYSIS AND DISCUSSION OF MODEL RESULTS

5.0 Introduction

Ghana's final annual electricity demands have been optimized in order to determine the least-cost energy supply options for the electricity sector. This chapter presents analysis and discussions on the modelling output based on the least-cost energy supply options for electricity generation over a thirty 30 year period (2017-2047). Based on the total system costs of the electricity system over the study period, two different scenarios were considered: Business as Usual (BAU) as the reference scenario and the High Economic Growth (HEG) scenario as detailed in the methodology.

5.1 Installed Capacity

The initial analysis of the BAU, otherwise known as the reference scenario has been set as the starting point used for the model to choose energy options for power generation based on the objective function of the study. That is, all forms of technologies have been given an equal chance of capacity installation without environmental or resource constraints.

The total installed capacity for the BAU and HEG is as shown in Figure 5.1 and Figure 5.2 respectively. The results for the shares of the installed electricity supply options by type of technology are also depicted in Table 5.1 and Table 5.2 of appendix 1. The model results indicate that Ghana's total electricity installed capacity will decrease gradually from 4,201.08 MW in the base year to 2,819.25 MW and 3,106.8 MW for BAU and HEG scenarios respectively in 2,047, as illustrated in Figure 5.1 and Figure 5.2. The annual decrease in installed capacity is equivalent to 1.27% and 0.97% on the average for the BAU and AEG scenario

projections. The decline in the installed capacity is as a result of limited demand. The shortfall in the installed capacity shows that there is limited electricity demand available to satisfy the capacity. Kichonge, et al. (2015) however argues that projected final electricity demand as most expected will require the total installed capacity to further increase from the base value. This brings about the increase in the installed capacity in the same direction as the projected electricity demand.

The results also show that Ghana's electricity generation will depend mostly on thermal power plants, hydro and solar systems. Biomass represents a small proportion of the total installed capacity whereas wind, coal, nuclear and tidal were not able to compete for all the scenarios. For the BAU scenario, the installation of thermal power plants, (Gas thermals (GT) and Combined Cycled Gas Thermal (CCGT)) decreased the total installed capacity from 2,625.6 MW in 2018 to 1551.22 MW in 2047. As represented in Table 5.1 of Appendix 1 for the BAU, the shares of the three hydropower plants in Ghana put together witnesses a stable installation capacity trend from 1370 MW to 1370 MW for the whole model period 2018 to 2047, showing its dominance over thermal production. This increased the shares of Hydropower plants from 36.04% in 2018 to 48.59% in 2047 and decreasing the shares of thermal generation from 58.55% in 2018 to 44.82% in 2047. Solar, on the other hand, increased marginally from 5.40% in 2018 to 6.58% in 2047.

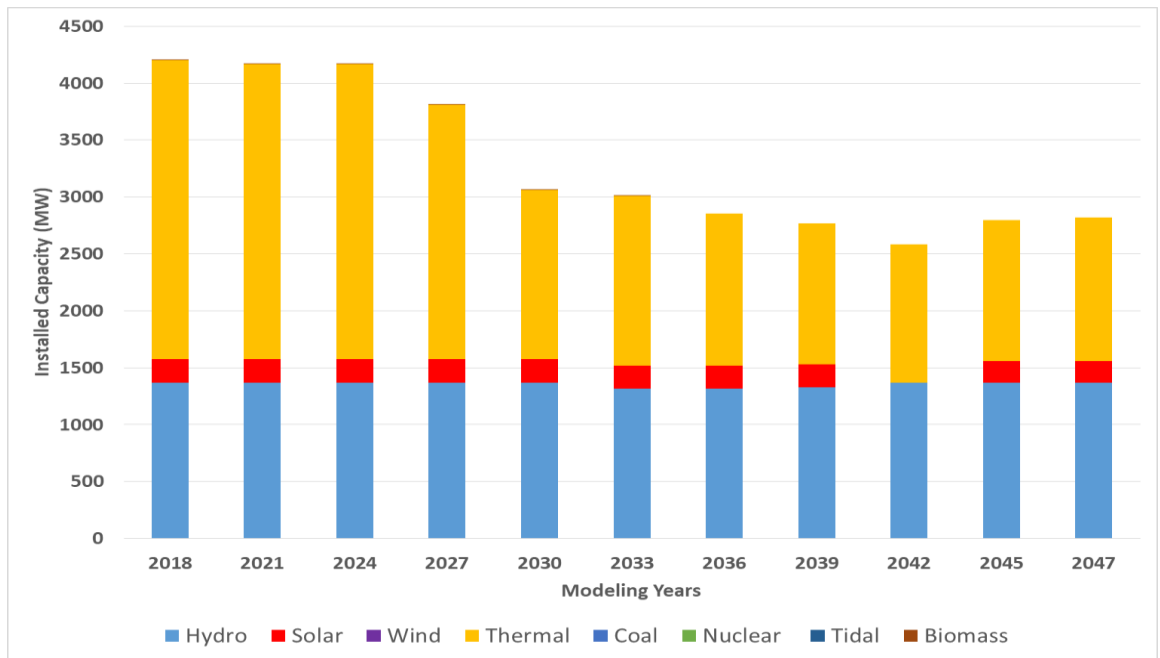


Figure 5.1: Least cost total installed capacity of baseline scenario (2018-2047)

Source: Author's estimation using MESSAGE model, 2018

As shown in Figure 5.2 for the HEG scenario, the installed electricity capacity from thermal power plants dominated the entire model years from 2,625.6 MW in 2018 to 1,263.67 MW in 2047, despite the dressing trend recorded. As shown in Table 5.2 of appendix 1, the thermal power plants had a share of 62.50% in 2018 decreasing to 49.93% in 2047. Hydropower plants placing second in terms of installed capacity still maintained a stable installation capacity of 1,370 MW for the entire period. The decreased in the shares of thermal power plants increased the shares of hydro marginally from 32.6% in 2018 to 44.10% in 2047. Solar on the other hand also increased marginally from 4.89% in 2018 to 5.97% in 2047.

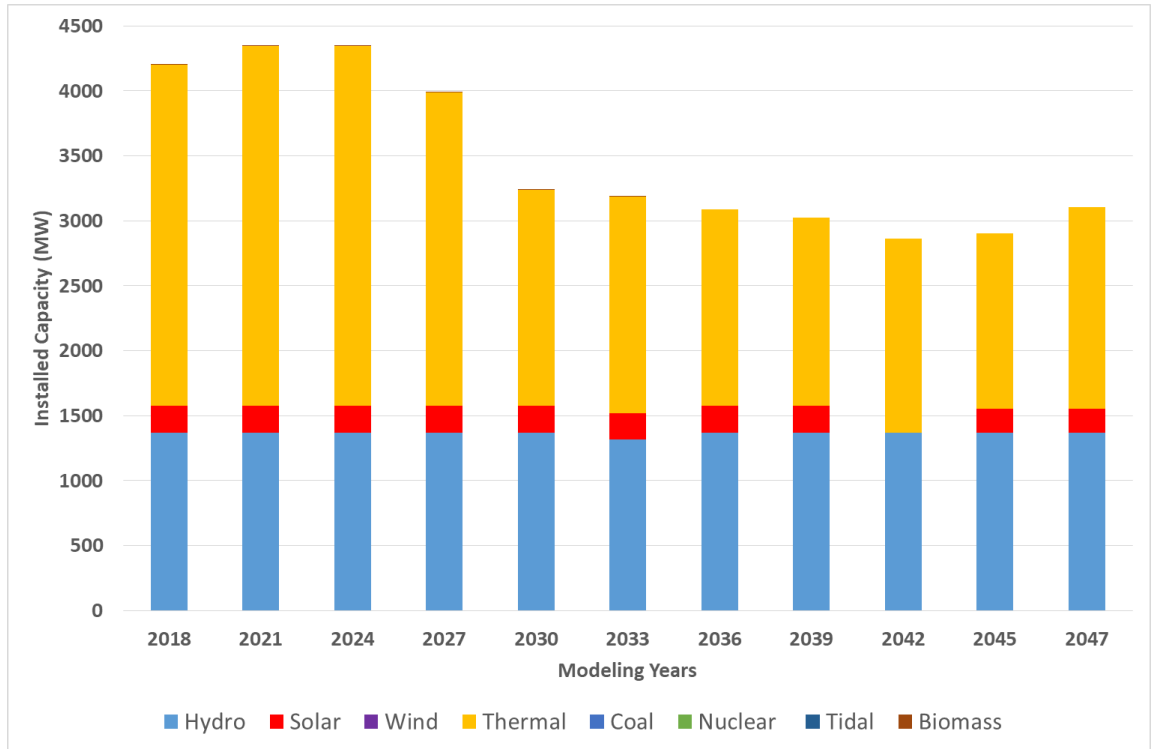


Figure 5.2: High Economic Growth (HEG) total installed capacity (2018-2047)

Source: Author's estimation using MESSAGE model, 2018

This development raises major concerns about zero-carbon emissions or climate mitigation technologies for electricity generation in Ghana. The main reason attributed to the decreasing trend is the potential constraints of Ghana's hydro potentials of recording low reservoir elevations despite the fact that it is the cheapest in operating costs (GRIDCo, 2016). This may also be as a result of difficulties associated with securing financial support as a major challenge to the power sector reform in Ghana (Kumi, 2017; Eshun, & Amoako-Tuffour, 2016).

5.2 Electricity Generation Mix

Like the installed electricity capacity, all forms of technologies have been given an equal chance of power generation without environmental or resource constraints under the BAU scenario. The electricity generation for the BAU and HEG

scenarios are represented as Figure 5.3 and Figure 5.4, respectively. The shares of electricity generation supply options result by type of technology is also shown in Table 5.3 and Table 5.4 for BAU and HEG of appendix 1 respectively.

Figure 5.3 and Figure 5.4 indicates that the BAU and HEG electricity generation expanded from 11,578.30 GWh and 10,480.57 GWh in 2018 to 13,110.49 GWh and 11,849.37 GWh, respectively in 2047. The annual growth rate of the generation capacity on the average is about 0.0043% and 0.42% for the BAU and HEG scenarios, respectively. The expansion in the model's results of the electricity generation capacity is confirmed by many optimization studies such as the works done by Awopone et al. (2017) and Kichonge, et al., (2015). Kichonge, et al., (2015) reported that Tanzania's electricity generation is expected to expand from 5,632 GWh in 2010 to 62,770 GWh in 2040.

As shown in Table 5.3 of Appendix 1 for the BAU scenario, the base year proportions in the electricity generation mix include hydro (59.99%), thermal (36.66%), solar (3.35%) and biomass (0.0017%). The results show the three hydropower plants in Ghana put together dominate the thermal power plants excluding coal power plants as modelled in Ghana's electricity generation mix. The solar and very little amount of biomass compensates for the remaining balance. The optimized results indicate the share of hydro decreased marginally from 59.99% in 2018 to 58.79 in 2047. The thermals, on the other hand, increased slightly from 36.66% in the base year 2018 to 40.39% in 2047. Hainoun, et al. (2010), in an effort to identify the challenges for the future economy of Syria, found a similar case of the Syrian energy system as certain to really on oil and gas for electricity generation. The conclusion was that, if stringent policies are not put in place for

the expected long-term electricity sector the economy is likely to face serious challenges in the energy sector (Hainoun et al., 2010).

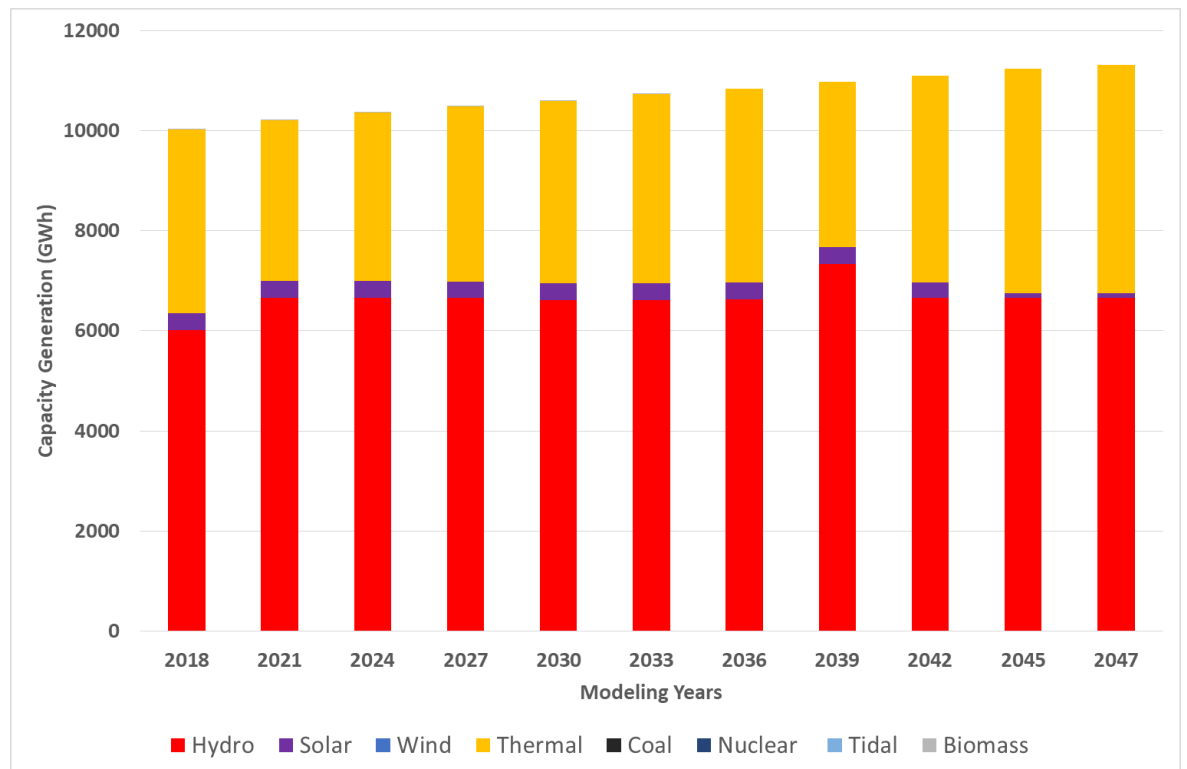


Figure 5.3: Least cost electricity generation for the study period (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

Table 5.4 of Appendix 1 represents the HEG scenario. The base year proportions in the electricity generation mix include hydro (59.28%), thermal (40.86%), solar (3.05%) and biomass (0.0016%). The results show that hydropower plants put together dominate the thermals power plants put together in Ghana’s electricity generation mix. Solar and biomass add up to the remaining balance. The least cost results indicate the share of hydropower generation decreased marginally from 59.28% in 2018 to 53.45% in 2047. Generation from thermal power plants increased from 40.86% in 2018 to 45.81% in 2047. Solar generation decreased

from 3.05% in 2018 to 0.75% in 2047, while biomass decreased slightly from 0.0016% in 2018 to 0.0015% in 2023.

The hydropower and thermal power technologies have shown the key role they both play in final electricity generation in Ghana. Kichonge, et al., (2015) confirms how these technologies have shown least-cost competitiveness in electricity generation in Tanzania. In effect, the model results signify the importance of hydro and thermal power technologies in the sustainable development of the electricity sector (Kichonge, et al., 2015).

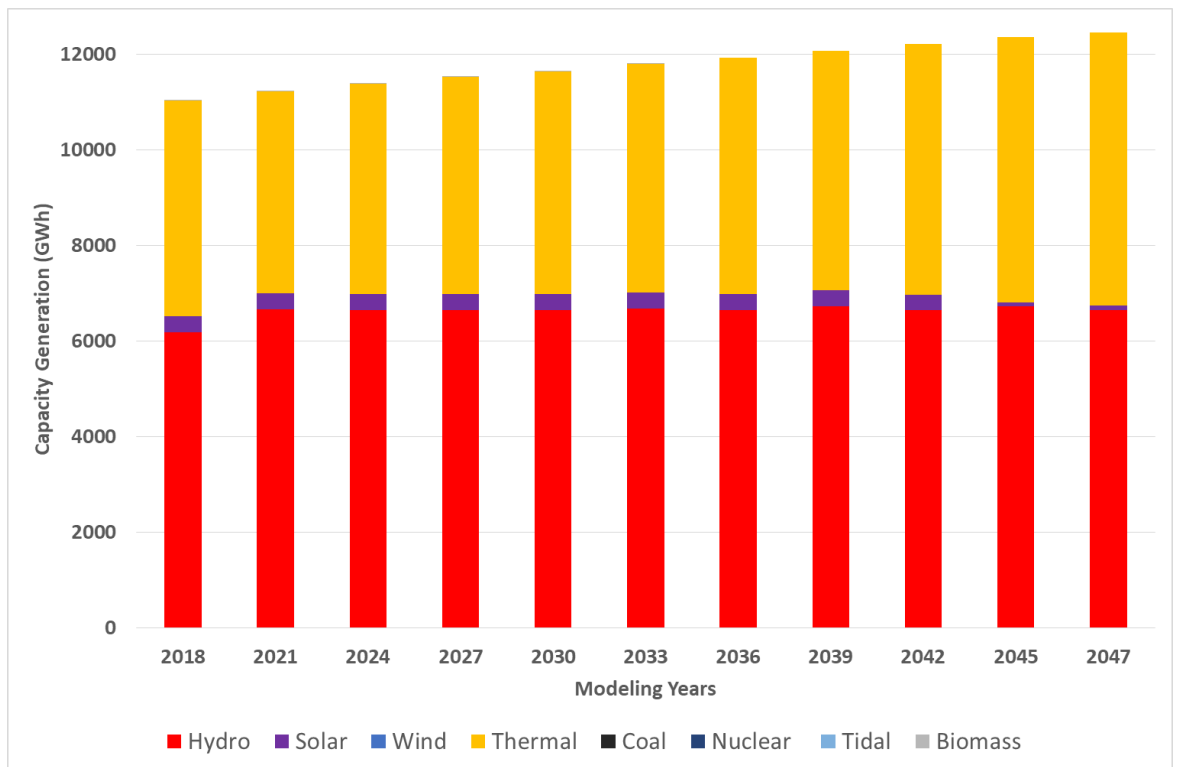


Figure 5.4: HEG electricity generation for the study period (2018-2047)

Source: Author's estimation using MESSAGE model, 2018

5.3 Carbon Dioxide Emissions of BAU and HEG Scenarios

Ghana as a Party to the United Nations Framework Convention on Climate Change (UNFCCC) and to the Kyoto Protocol is dedicated to meeting its commitments in order to contribute its fair share to the attainment of the objective of the Convention (UNFCCC, 2015). In 2015, Ghana at the multilateral level reaffirmed its resolution to support global efforts to define a common future that seeks to give equal opportunities to all nations and their citizens, to pursue and realise their future aspirations. In view of the above and in accordance with Decisions 1/CP.19 and 1/CP.20, Ghana communicated the intended nationally determined contribution (INDC), otherwise known as Nationally Determined Contribution (NDC) and an associated explanatory note to facilitate the clarity, transparency, and understanding of the country's contribution. Based on the national circumstances, Ghana has put forward mitigation and adaptation actions in its INDC. The inclusion of both mitigation and adaptation in the INDC resonate with the medium-term development agenda (Ghana Shared Growth Development Agenda II–GSGDA 2), the anticipated 40-year socio-economic transformational plan and the universal sustainable development goals (UNFCCC, 2015).

Ghana's emission reduction goal is to unconditionally lower its greenhouse gasses (GHG) emissions by 15% relative to a business-as-usual (BAU) scenario emission of 73.95 MtCO_{2e} by 2030 (UNFCCC, 2015). In addition, an additional 30% emission reduction is attainable on condition that external support is made available to Ghana to cover the full cost of implementing the mitigation action.

Decisions regarding the choice of power plants have largely been influenced by the environmental friendliness of the plants. Based on Ghana's commitment to NDC,

15% and 30% of the total emissions were computed and used as a constraint on the modelling system. The CO₂ emissions when applied to the model, power plants that are producing CO₂ will either limit their production or shut-down to allow for a more environmentally friendly generation system to operate.

Figure 5.5 indicates that the total CO₂ emission rises from 1599.75-kilotonnes of CO₂ in 2018 to 2056.14-kilotonnes of CO₂ in 2047. The rise in CO₂ emission in the BAU scenario represents an annual average growth of 7.6%. The higher CO₂ emissions in the BAU scenario are highly influenced by higher electricity demands, which resulted in optimal capacity additions of thermal power plants that run on fuels such as NG, DFO, LNG, LPG, and LCO.

On the contrary, Ghana's Climate Change Actions sought to increase the proportion of zero-carbon sources such as renewable energy including hydro sources with the aim of diversifying the country's energy mix (UNFCCC, 2015).

As shown in Figure 5.5, total CO₂ emissions set under the NDC 15% emission reduction increased from 1359.79-kilotonnes of CO₂ in 2018 to 1747.72-kilotonnes of CO₂ in 2047, while total CO₂ emissions set under the NDC 30% emission reduction increased from 951.85-kilotonnes of CO₂ in 2018 to 1223.40-kilotonnes of CO₂ in 2047.

The result after the NDC 15% and 30% emissions reduction are discussed subsequently.

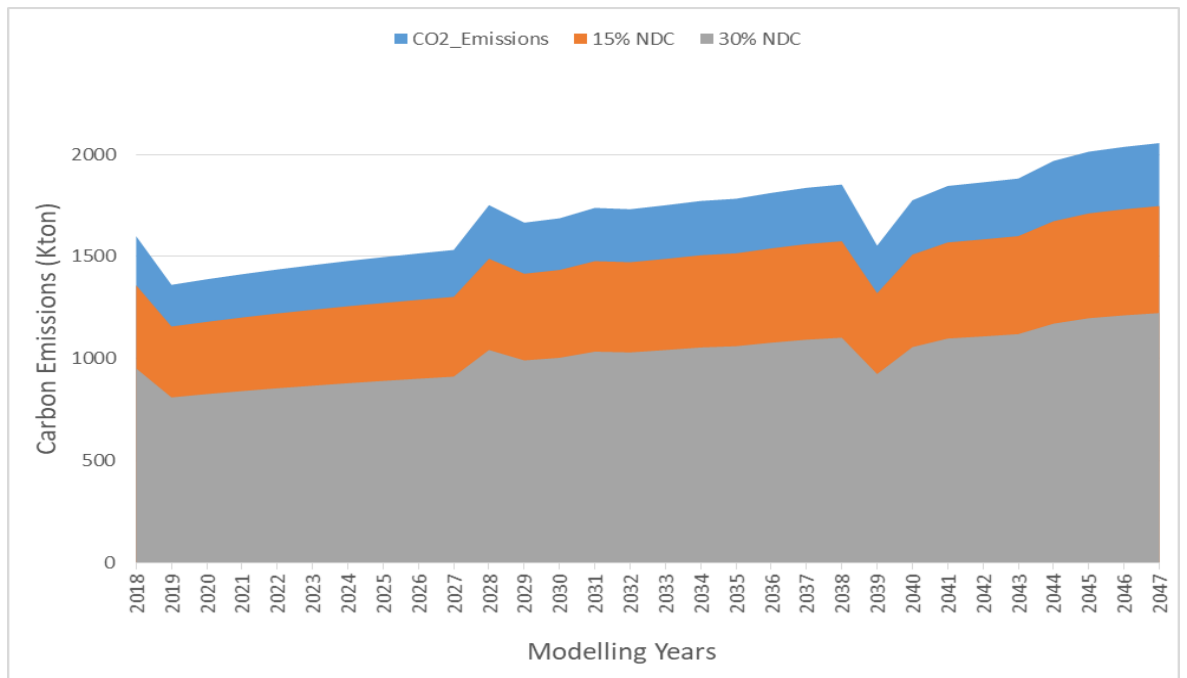


Figure 5.5: Least cost projected CO₂ emissions (2018-2047)

Source: Author's estimation using MESSAGE model, 2018

The total installed electricity capacity for the BAU and HEG NDC 15% emission reduction target scenarios is shown in Figure 5.6 and Figure 5.7 and the shares of installed electricity supply options results by type of technology are presented as Table 5.5 and Table 5.6 of Appendix 1 respectively. The illustration in Figure 5.6 and Figure 5.7 shows that Ghana's total electricity installed capacity decreased from 3,801.08 MW and 4,201.08 MW in the base year 2018 to 3,039.62 MW and 3,380.45 MW in 2047 respectively.

For the BAU scenario, Ghana's electricity generation depended much on thermal installed capacity but relieved to hydropower installation at the end of the modelling year, 2047. As represented in Table 5.5 of appendix 1, CO₂ emission reduction of the NDC 15% emission reduction scenario brought about a marginal increase in installations for hydro, wind and solar power plants. This confirms the study by Awopone et al. (2017) for Ghana. It was argued that, with a

comprehensive implementation of energy efficiency measures, renewable energy technologies are capable of contributing more than 70% of Ghana’s needed electricity generation by 2040 (Awoopone et al., 2017). The thermal installations had a decrease in their shares from 58.55% in the base year, 2018 to 39.73% in 2047. Hydropower installations increased marginally from 36.04% in 2018 to 45.67% in 2047. Wind installations increased tremendously from 2.68% shares in 20121 to 9.09% in 2047. The decrease in thermal installations is attributed to the high emissions from gas power plants. The zero carbon sources, such as wind, solar and hydro, recording some marginal increases are attributed to the 15% endpoint emission reduction set by the NDC.

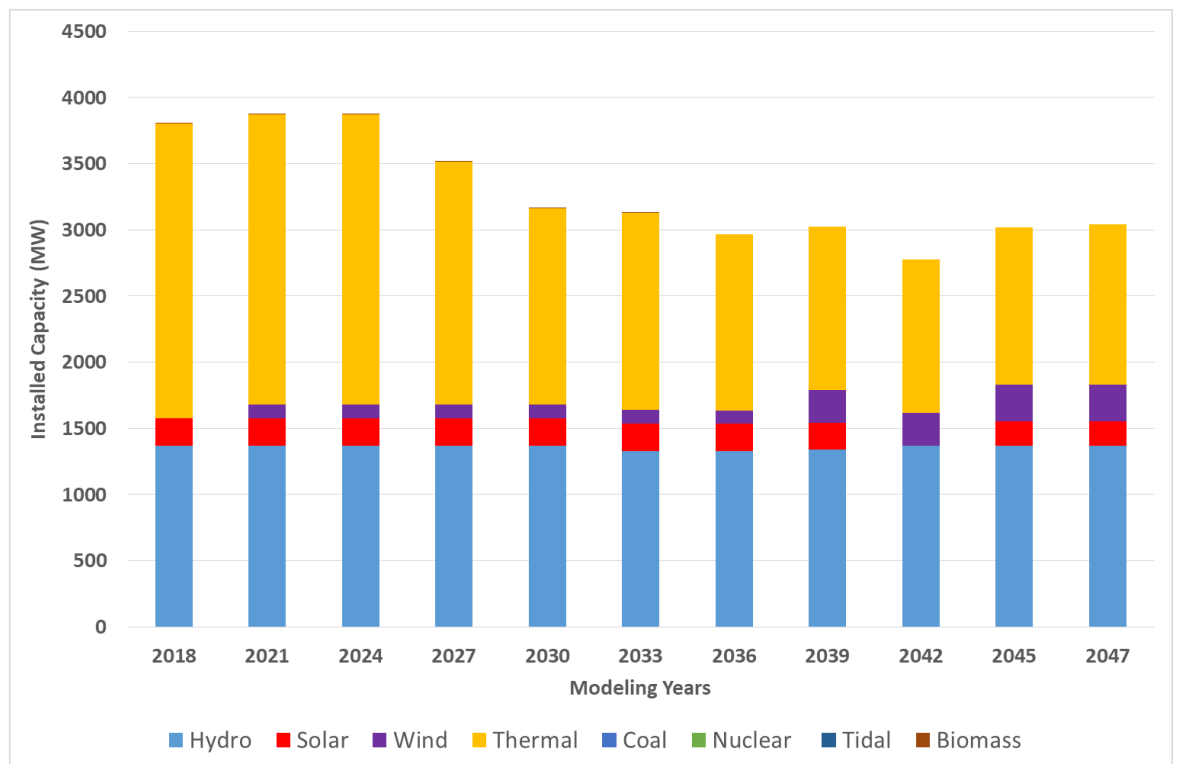


Figure 5.6: NCD 15% emission reduction total installed capacity (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

For the HEG scenario, presented as Table 5.6 of appendix 1, all thermal units put together still dominate Ghana’s electricity installation capacity for the whole model period. The thermals installed capacity however decreased from 62.50% in 2018 to 43.183% in 2047. Hydro, as usual, increased marginally from 32.61% in 2018 to 40.53% in 2047. The wind made an encouraging increase from 2.43% in 2021 to 10.15% in 2047. Solar, though picked up very well in 2018, its increase was however very little from 4.89% in 2018 to 5.49% in 2047.

The general indication is that Ghana’s achievement of significant economic and environmental sustainability of the energy and electricity sector will require more penetration of zero-carbon technologies (Awopone et al., 2017).

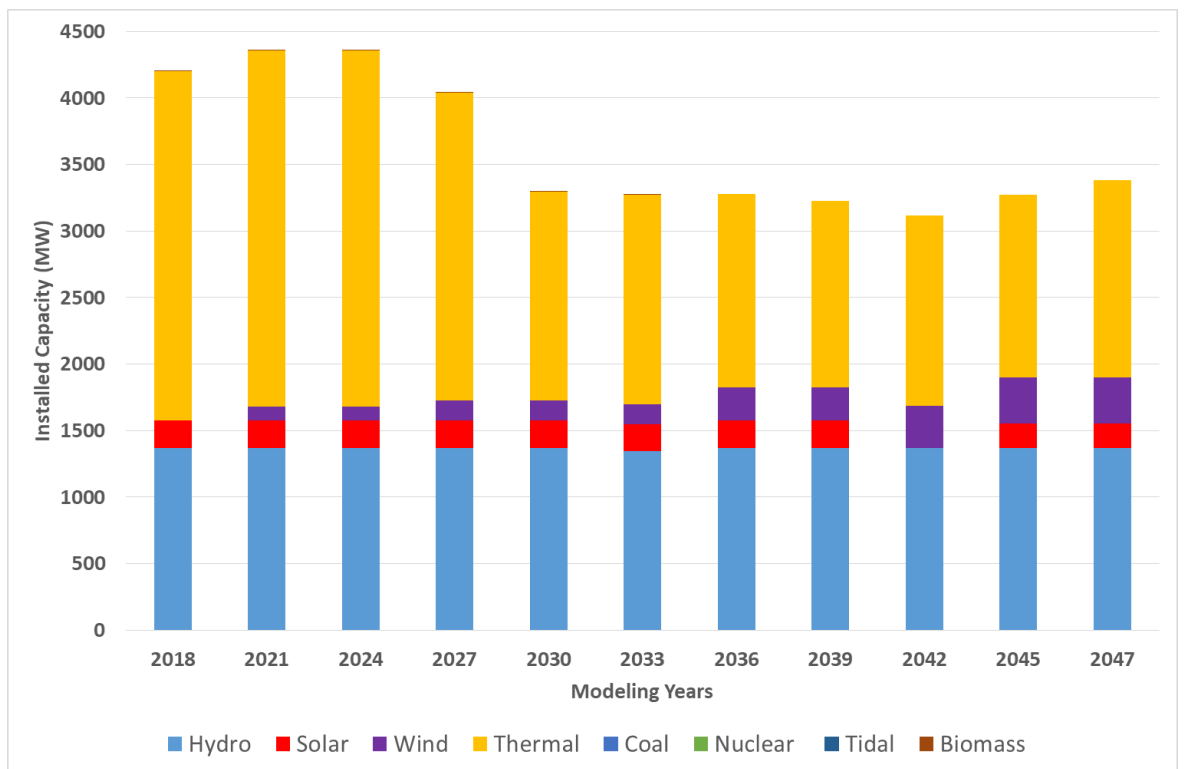


Figure 5.7: HEG NCD 15% emission reduction total installed capacity (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

The total electricity generation for the BAU and HEG NDC 15% emission reduction scenarios is shown in Figure 5.8 and Figure 5.9 respectively. The share of electricity generation supply options by type of technology is also presented as Table 5.7 and Table 5.8 of appendix 1. As presented in Figure 5.8 and Figure 5.9, electricity generation expanded from 10,022.78 GWh and 11,025.59 GWh in the base year 2018 to 11295.95 GWh and 12422.84 GWh in 2047 for the BAU and HEG scenario, respectively.

As depicted in Table 5.7 of appendix 1, the electricity generation mix of the base year share includes hydro (50.80%), thermal (45.85%), solar (3.35%) and biomass (0.0017%). The results show hydropower plants dominate thermal power plants in Ghana's electricity generation mix with solar, wind and biomass compensating for the balance. The results also showed that hydropower plants saw an increase from 50.80% in 2018 to 58.90% in 2047. Thermal power plants, on the other hand, decreased from 45.85% in 2018 to 34.26% in 2047. Solar decreased from 3.35% in 2018 to 0.82% in 2047 while wind increased marginally from 5.11% in 2018 to 6.02% in 2047.

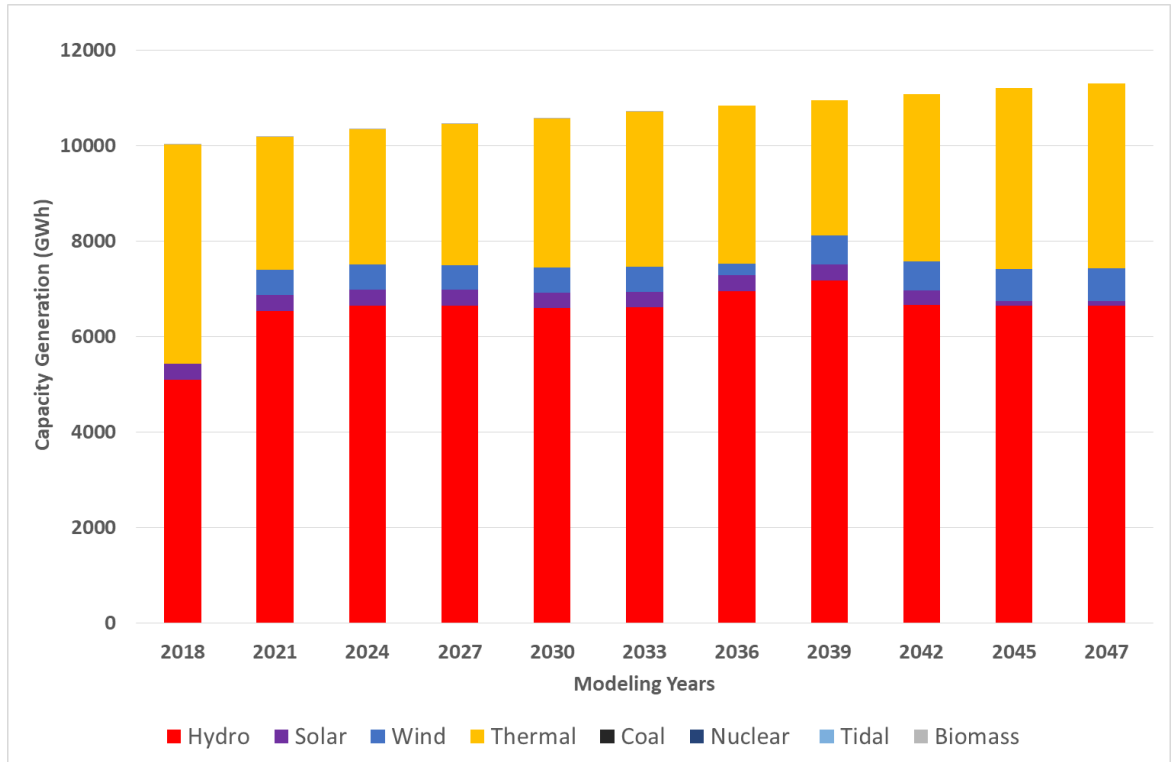


Figure 5.8: NDC 15% emission reduction electricity generation (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

As depicted in Table 5.8 of appendix 1, the electricity generation mix of the HEG base year share includes thermal (54.43%), hydro (42.51%), solar (3.05%) and biomass (0.0016%). In this scenario, thermals dominate the generation capacity from 54.43% in 2018 but relieved its position to hydropower generation in 2021. Electricity from hydropower generation began to dominate from 59.54% in 2021 and decreased to 53.59% in 2047. Renewables- hydropower, wind, solar and biomass generation competed very well in the generation mix but in a decreasing manner.

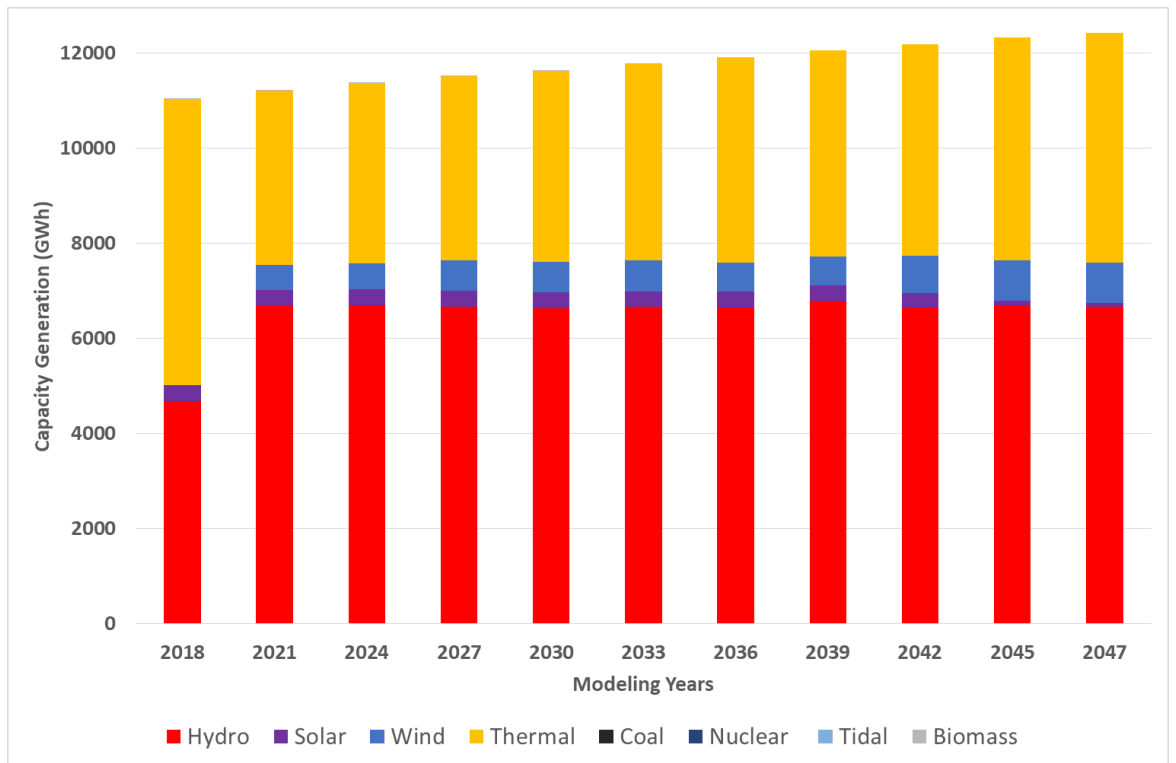


Figure 5.9: HEG NDC 15% mission reduction electricity generation (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

The total installed electricity capacity for the BAU and HEG NDC 30% scenarios is represented in Figure 5.10 and Figure 5.11 while the share of installed electricity supply options results by type of technology is depicted in Table 5.9 and Table 5.10 of Appendix 1.

In the BAU scenario, as at the end of the modelling period, the share of wind installation capacity has increased very well from 2.74% in 2021 to 21.82% in 2047. Hydropower plants became the highest generation source of power, compared to the thermal power generation at the end of the model year 2047, with 32.60% and 40.14%, respectively.

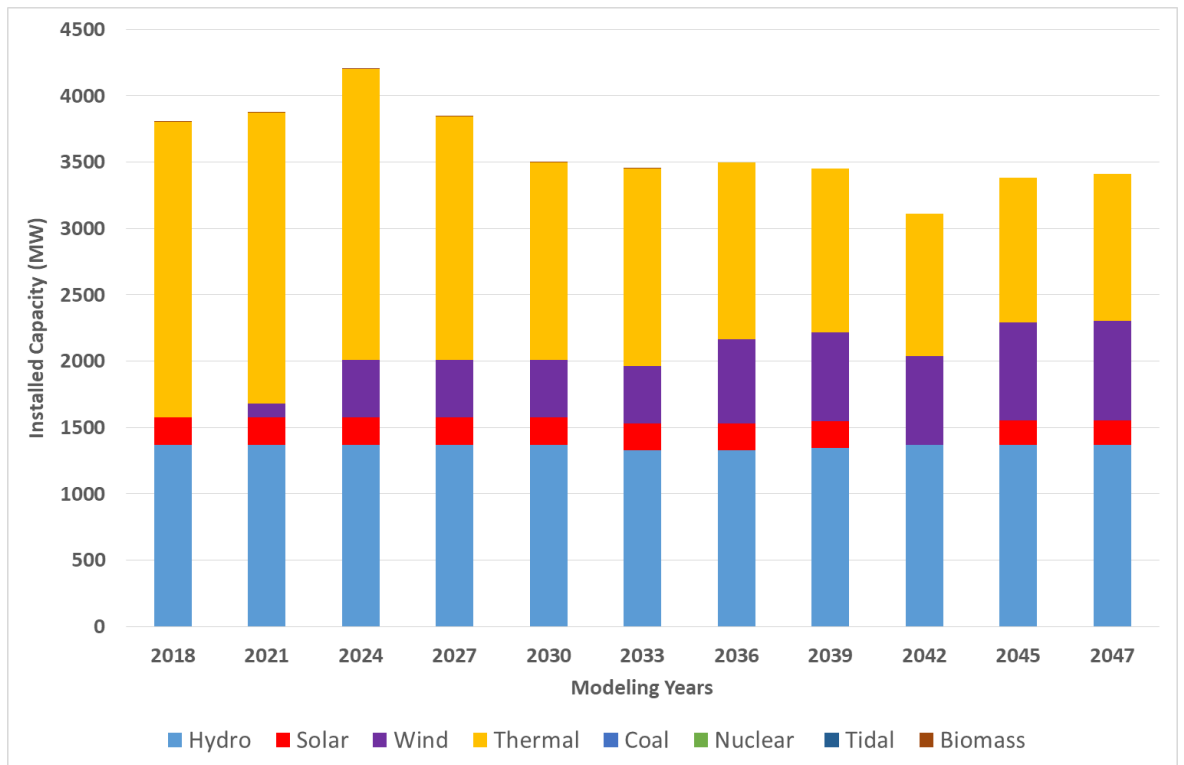


Figure 5.10 NDC 30% emission reduction total installed capacity (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

As represented in Table 10 of Appendix 1, for the AEG scenario, the share of thermal power plant installations dominated all other power plants at a decreasing rate, from 62.50% to 35.58% for the modelling period 2018 to 2047, leaving hydro in the second position which increased marginally from 32.61% in 2018 to 35.70% in 2047. The increase from wind power installation outstripped solar power installation from 2.74% in 2018 to 23.89% in 2047 for wind and 4.89% in 2018 to 4.84% in 2047 for solar installation capacity.

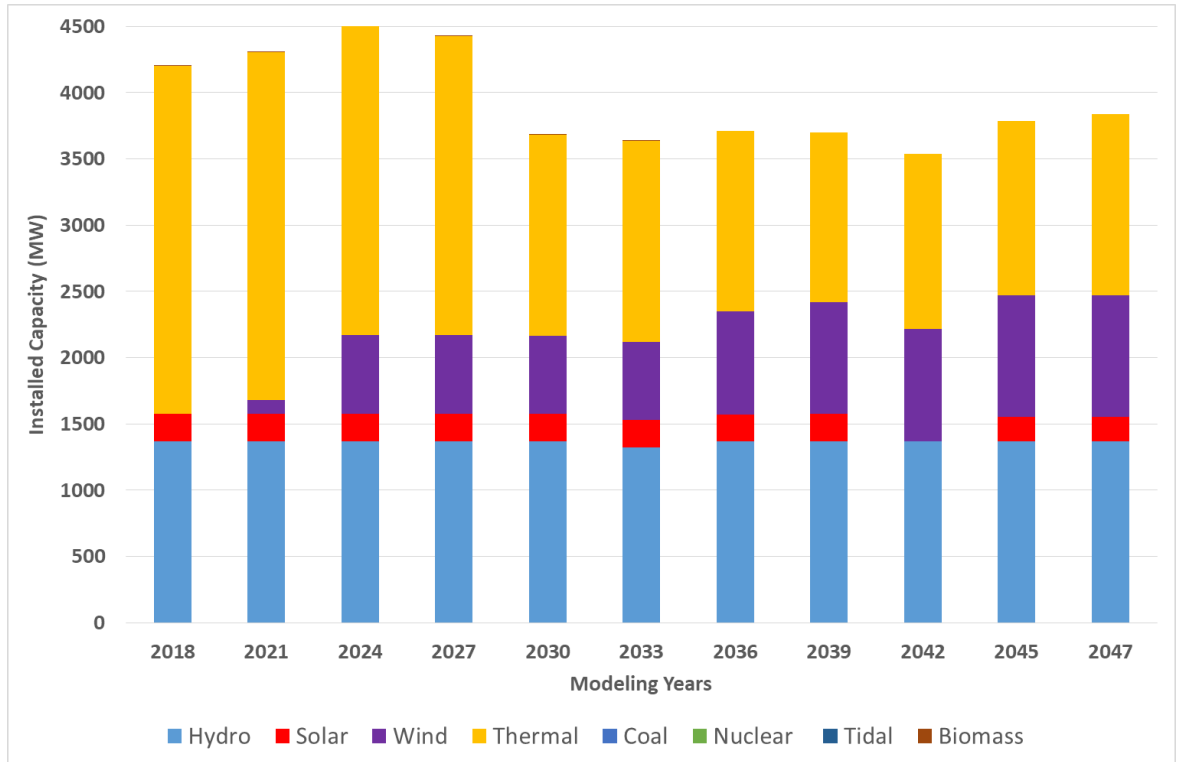


Figure 5.11 HEG NDC 30% emission reduction total installed capacity (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

The total electricity generation for the BAU and HEG scenarios after NDC 30% emissions reduction is shown in Figure 5.12 and Figure 5.13 and the share of electricity generation supply options by type of technology in Table 5.11 and Table 5.12 of appendix 1. Figure 5.12 and Figure 5.13 shows that the least cost electricity generation expanded from 11022.42 GWh and 11022.42 GWh in 2018 to 11,260.31 GWh and 12,379.20 GWh in 2047 for the BAU and HEG scenarios respectively.

As the main power generation, despite the initial generation capacity of 78.63% and 80.79% for the thermals in the base year for the BAU and HEG scenarios, the generation capacity shifted to the dominance of hydropower generation at the end

of the modelling period, leaving thermals generation capacity at 23.93% and 27.21% and hydropower at 58.97% and 53.83% for the BAU and HEG scenarios respectively in 2047. Wind also made a remarkable increase in its generation from 5.22% and 4.75% in 2018 to 16.27% and 18.21% for the BAU and HEG scenarios respectively in 2047.

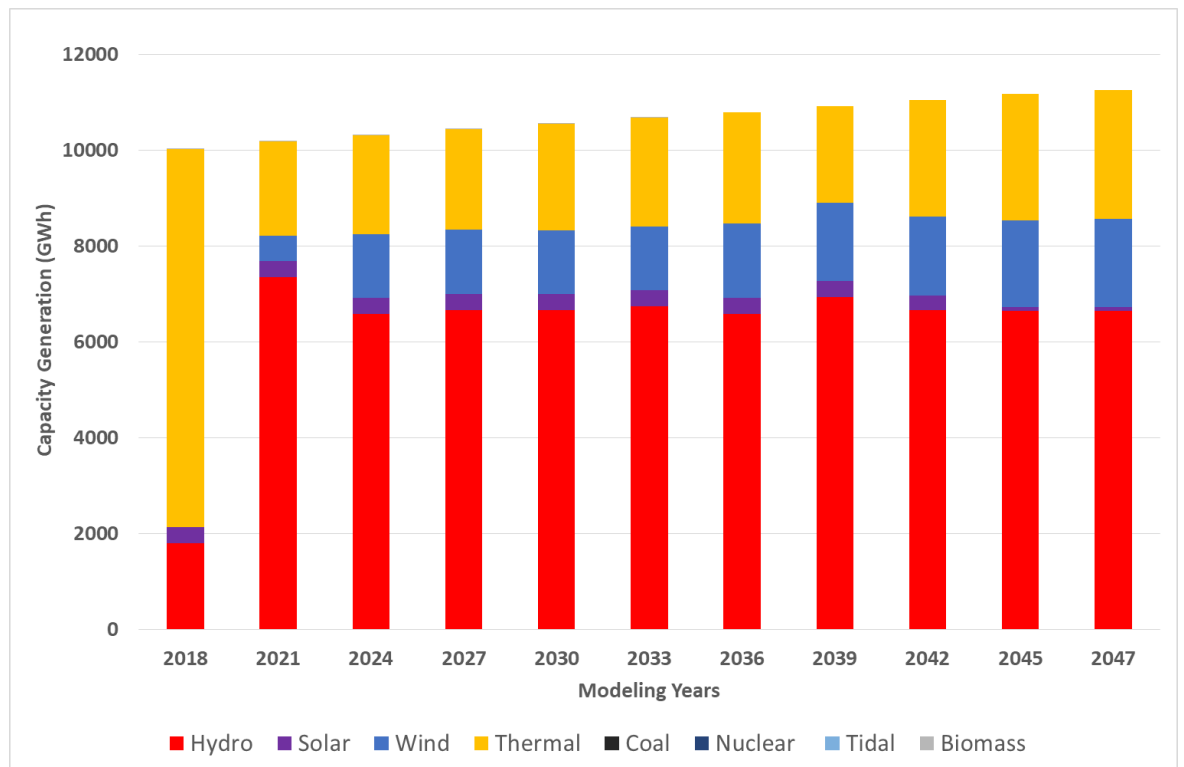


Figure 5.12 NDC 30% emission reduction electricity generation (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

In general, if Ghana is to internalise the cost of power production related to air pollution damage, clean and advanced technologies are likely to increase their market share in the country’s electricity production. The study by Klaassen & Riahi (2007) reaffirms that renewables and other clean technologies will have the prospects of significant increases at the expense of high emitting power plants.

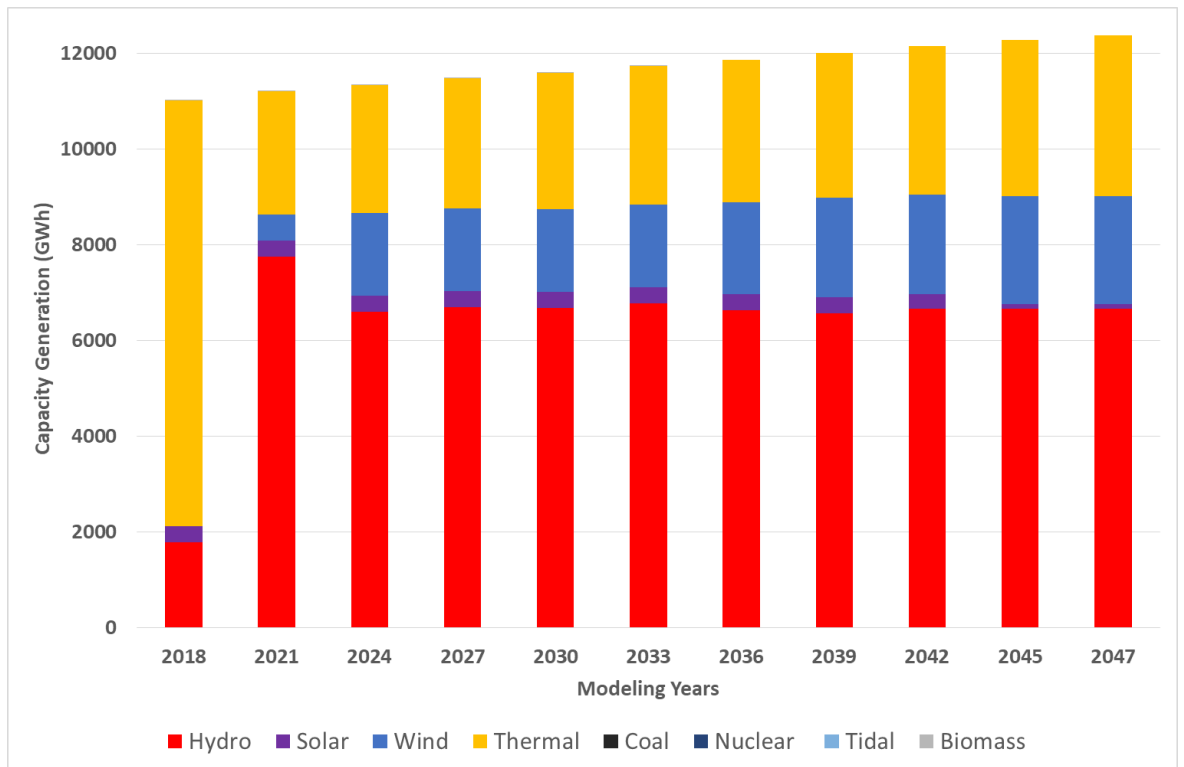


Figure 5.13 HEG NDC 30% emission reduction electricity generation (2018-2047)

Source: Author’s estimation using MESSAGE model, 2018

5.4 Economics of Scenarios

5.4.1 Annual Investment Cost

The cost of power generation is expected to give the same net present cost as the actual cash flow sequence associated with electric power generation.

The least-cost modelling results as presented in Figure 5.14 and Figure 5.15 show the investments needed annually to install generation capacities under the BAU and HEG scenario. The Figure best describes the investments made annually on new generations.

As indicated in Figure 5.14 for the BAU scenario, from 2018 to 2023, investments of about 119.4 million USD for no emissions cap, 326.87 million USD for NDC 15% emission reduction and 757.18 million USD for NDC 30% emission reduction

is required. Further, from 2044 to 2047, investment of 58.072 million USD need to be made for the no emissions cap, 79.367 million USD for NDC 15% emission reduction scenario and 79.830 million USD for the NDC 30% emission reduction scenario. As expected, the NDC 30% emission reduction scenario recorded the highest amount of investment cost throughout the years.

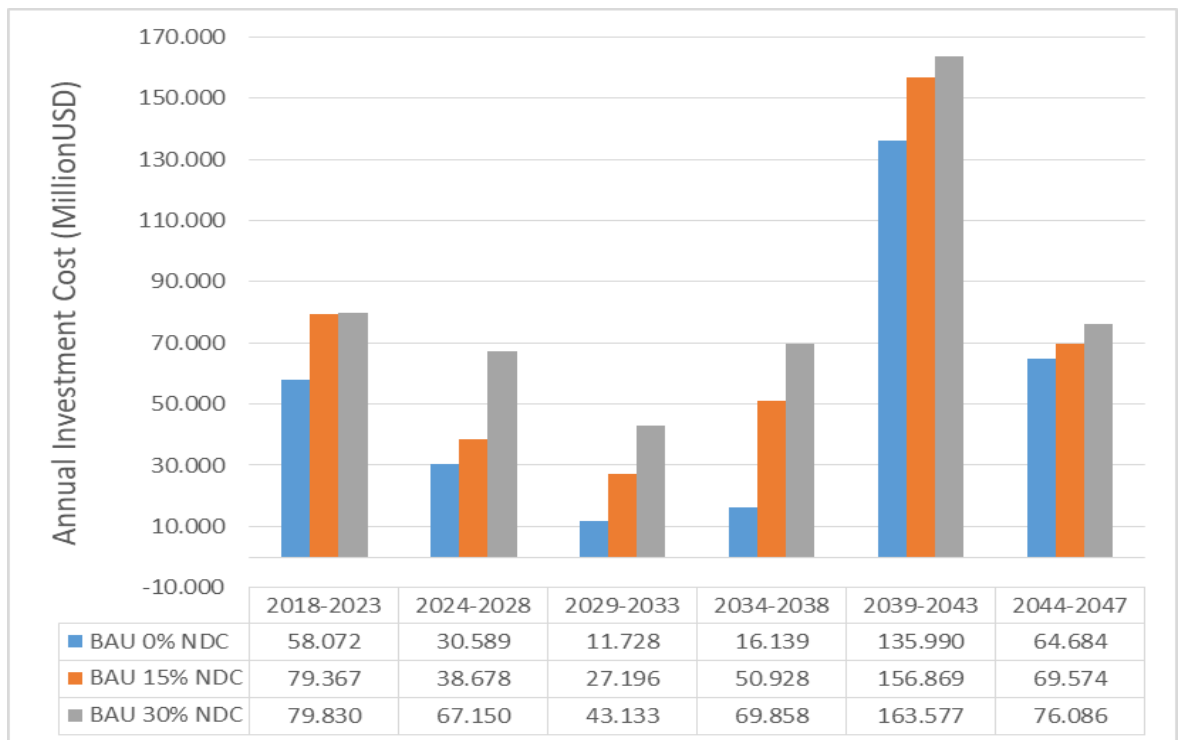


Figure 5.14 Annual investment costs of BAU

Source: Author’s estimation using MESSAGE model, 2018

The annual investment cost for the HEG scenario follows a similar trend as the BAU scenario. The HEG scenario for the NDC 30% emission reduction scenario dominates the yearly investment costs required for electricity generation. It can be affirmed that the higher investment costs required in this scenario are an indication of the investment requirements to mitigate carbon dioxide emissions resulting from electricity generation. Hogan (2002), in the diversification of energy systems’

results, found that annual state-wide GHG emissions are 8-46% lower than 1990 levels by 2030 and 59-84% by 2050. This confirms the huge investments needed to satisfy NDC 30% emissions reduction targets. The integration of modern energy technology development (Rakshit et al., 2018) is key to allow for energy modelling on a large scale built on the fundamentals of research in energy, economics and environment (Hogan, 2002). This confirms Ghana’s intention to mobilize about USD 22.6 billion investment from both domestic and international public and private sources for climate change mitigation and adaptation (UNFCCC, 2015).

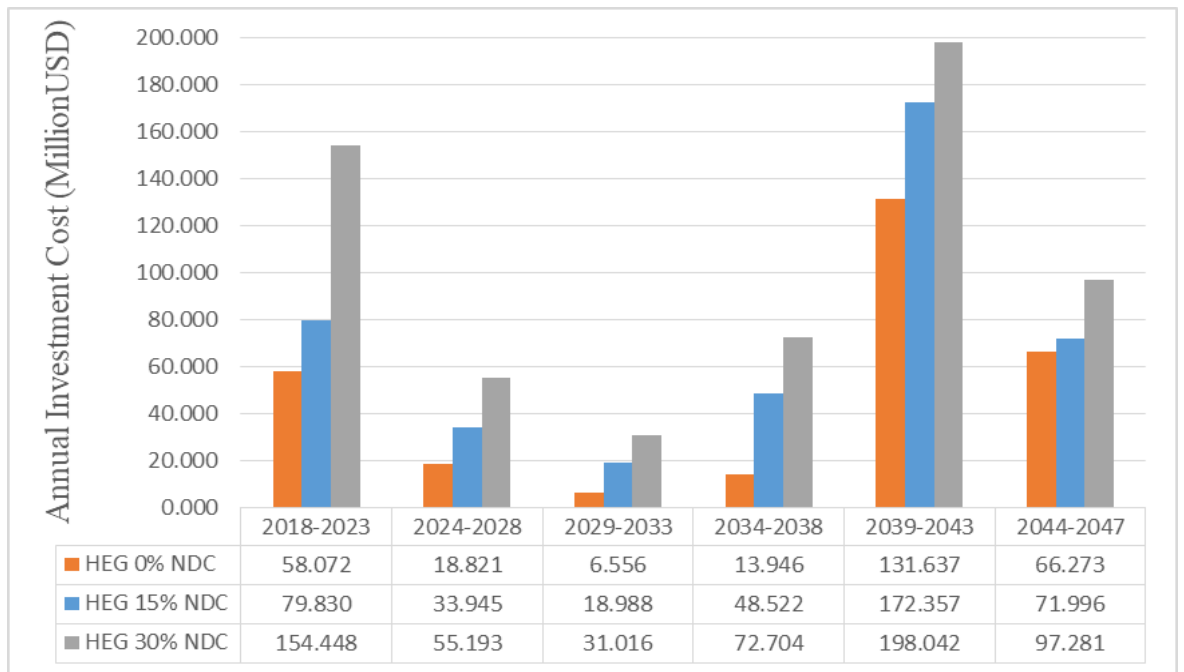


Figure 5.15 Annual investment costs of HEG

Source: Author’s estimation using MESSAGE model, 2018

5.4.2 Average Generation Costs

The cost of generating electricity includes the capital cost, the financing charges, and the production or operating costs (including fuel and maintenance of the technology) at the point of connection to the electricity grid.

In meeting Ghana’s final electricity demand under the BAU and HEG scenarios, the average generation cost required has been computed from the least cost generation results. The average generating cost of all power plants is presented as Figure 5.16 and Figure 5.17 on yearly basis, for the BAU and HEG scenarios respectively.

Figure 5.16 indicates that, from 2018 to 2023, it will require 1.24 billion USD without emissions cap to generate electricity, whereas it will require 1.46 billion USD and 1.60 billion USD for emission scenarios of NDC 15% and 30% emission reduction target to generate electricity to meet the growing demand. Further, between 2044 and 2047, it will require an investment of 0.42 billion USD, 0.56 billion USD and 0.74 billion USD to generate electricity under the BAU without an emission cap, NDC 15% emission reduction and NDC 30% emission reduction target respectively.

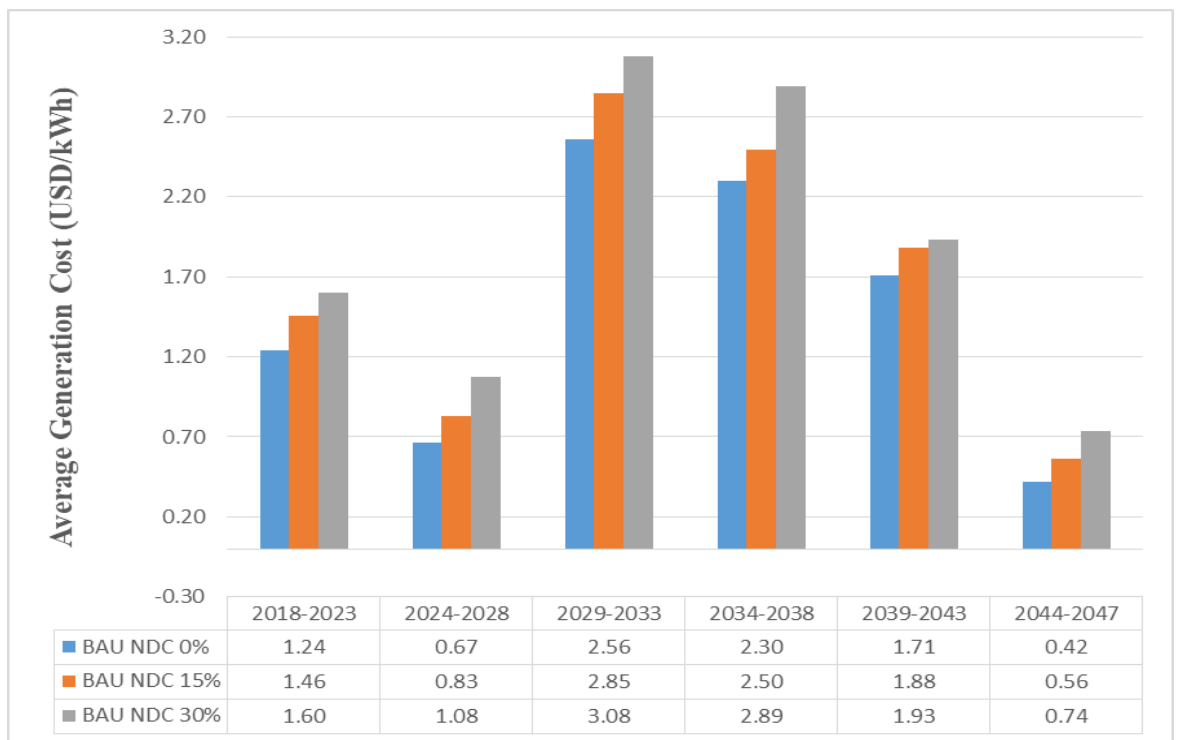


Figure 5.16 Average Generating costs of BAU

Source: Author’s estimation using MESSAGE model, 2018

The HEG scenario presented in Figure 5.17 shows that between 2034 and 3038, an investment of 3.64 billion USD will be required for no emissions cap, 6.01 billion USD for the NDC 15% emission reduction target and 6.85 billion USD for the NDC 30% emission reduction to generate electricity to meet the demand. It is clear that without any emission target, the average generating cost of electricity is cheap compared to set targets for CO₂ emissions reductions.

The average generation cost recorded under the BAU and HEG scenarios indicates the higher cost needed under the NDC 30% emissions reduction target. This shows why Ghana’s development strategy should not solely emphasize economic benefits at the expense of long-term electricity planning, environmental quality and social well-being (Basiago, 1998).

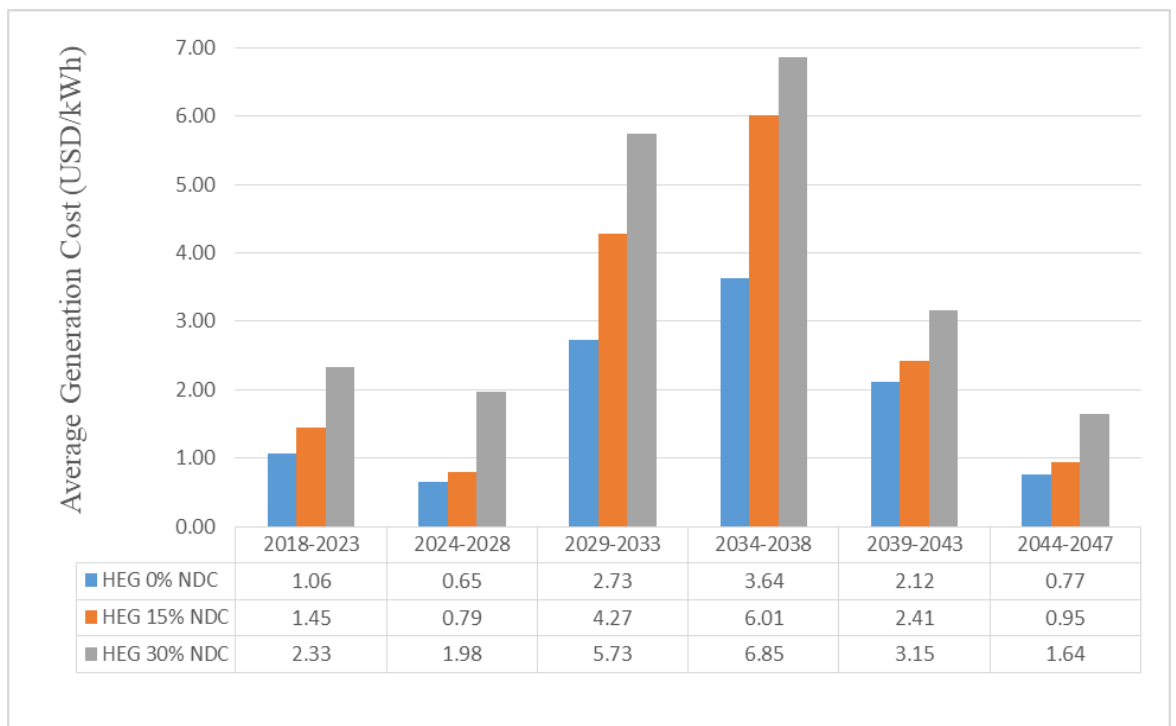


Figure 5.17 Average Generating costs of HEG

Source: Author’s estimation using MESSAGE model, 2018

5.5 Summary

The chapter presented and discussed the results of the model. In general, continues decline in the total installed capacity for the study period (2018 to 2047), indicates there is overcapacity of electricity generation compared to the demand. This resulted in the decline in the installed capacity of power plants. The higher proportion of hydropower and thermal (that run on NG, LCO, DFO, LNG, HFO, and LPG) plants in Ghana's electricity generation mix is imminent due to lower investment and fuel costs compared to other technologies considered, such as nuclear. The coal and tidal power plants did not feature in the generation mix because of their new generation and lower demand capacity throughout the model period. The continued decline in hydropower plant proportions from the base year is due to the presumed new investment in thermal power plants such as Gas thermals (GT) and Combined Cycled Gas Thermal (CCGT) power plants.

The least-cost results have shown implications concerning annual and the average generation cost for electricity generation in Ghana. The average generation cost of electricity gave an insight into the detailed generation cost of power plants on a yearly basis.

CHAPTER SIX

SUMMARY, CONCLUSION AND POLICY RECOMMENDATIONS

This chapter presents a summary of the study and draws a conclusion. The chapter also includes policy recommendations from the findings and limitations of the study.

6.1 Summary of the study

Electricity has contributed to the development of many nations at the early stages of their development and continue to be a key developmental component in both developed and developing nations (Hargreaves, A. & Shaw, P., 2007). Infrastructure (schools, hospital, transportation, etc) development process has a positive link with affordable and clean electricity generation.

Therefore, the contribution of electricity to development cannot be underestimated. In this regard, there exists a growing interest in the supply of electricity to all sectors of the Ghanaian economy. Many governments have continuously planned the supply of affordable and clean electricity to meet the growing citizenry demands. The environmental issues and economic cost in relation to power generation is, however, a huge bottleneck to the aspirations of Ghana governments. This study looks at the energy diversification policy of the government of Ghana by including all the energy options that are needed to supply electricity. These included coal, hydro, renewables (solar, wind, tidal and biomass), nuclear and thermal power plants.

The review of existing literature provided insights into the optimal supply of electricity for the long-term and how electricity supply depends largely on technical, economic and environmental parameters. The energy optimization modelling system also provided the systems modelling needed to supply electricity at the least cost.

Furthermore, the study presented an overview of policies and reforms in Ghana's electricity sector since 1960. The overview revealed that electricity generation in Ghana has gone through a series of challenges despite governmental strategies to deal with the power crises. The prevailing challenges of the electricity sector in Ghana since 1960 has been persistent as a result of limited power systems planning and modelling for optimal electricity supply in a low carbon environment.

The study employed the development of scenarios (BAU and HEG) and an empirical methodology in the modelling. The employment of the empirical methodology aided the setup of the optimized objective function for the electricity supply model, under a set of constraints (electricity demand-supply balance, the capacity requirement of technologies and the resource composition), that define the feasible region containing all possible solutions of the problem.

6.2 Conclusion

In general, the model had a limited demand as compared to the available capacity to satisfy the demand. This situation caused a declined in the installed capacity at the end of the modelling period, 2018 to 2047. The situation of limited demand

also caused new generations such as coal, tidal and nuclear not to feature at all in the modelling period.

Thermal power plants dominated in terms of installed capacity. Hydropower plants put together, however, dominated in the electricity generation mix in Ghana during the study period. The introduction of NDC 15% and 30% emission reduction targets, showed hydro and renewables such as wind will make a remarkable increase in generation from 2021 to 2047.

The annual investment analysis indicated that higher investment cost is required in the years 2039 to 2043 for the country's power sector. The highest average generation cost is also required between the years 2029 to 2038. It, however, requires a maximum generation cost of 3.64 billion USD, 6.01 billion USD and 6.85 billion USD to generate electricity under HEG for the no emission cap, 15% NDC emission reduction target and 30% NDC emission reduction target for the years 2034 and 2038, respectively.

Both scenarios, BAU and HEG, indicated that the NDC 30% emission reduction target requires the highest investment for electricity generation throughout the modelling period, 2018 to 2047. The least-cost modelling results on the annual investment and average generation cost have concluded that meeting final electricity demands without considerations of environmental impacts concerns is the cheapest. In general, the increase in Ghana's market share for clean technologies will require the internalisation of the cost of power production related to pollution damage.

6.3 Policy Recommendations

Based on the findings of this study, the following policy recommendations are therefore suggested.

To start with, Ghana's long-term electricity generation mix requires a major commitment from Ghana government, in terms of resources to equip research studies such as this for effective energy planning since energy planning studies are limited in the country. In view of this, long-term studies and planning in the electricity sector are key to allow for the short to medium term plans to fit into the former successfully for implementation. The long-term electricity planning should be reviewed on a short to medium term basis to keep it current and relevant for execution.

Second, the least cost modelling results have concluded that meeting final electricity demands without considerations of environmental impacts concerns is cheaper. For Ghana's electricity system investment, policymakers should not strive at using only such option but rather balance the capital investment costs and environmental concerns in energy planning and implementation.

Third, carbon dioxide mitigation is global, it may, therefore, be costly for Ghana government to mitigate at NDC 30% emission reduction target. Hence the recommendation for policy makers to take critical measures to mitigate at NDC 15% emission reduction target as against electricity generation with or without external support.

Finally, despite the NDC 15% and 30% CO₂ emission target, it is recommended for the government of Ghana to strategize critically for the inclusion and penetration of low or carbon free generation technologies, such as renewables and nuclear. This will allow for more inclusion of zero-carbon technologies in Ghana's electricity generation mix, per the country's unconditional emissions reduction goals.

6.4 Limitations of the study

The major limitation of the study has to do with the demand projections for electricity supply modelling. The study did not conduct its own demand projections due to time constraint. The energy demand projections for the country is usually carried out by the energy commission. Strategic National Energy Policy (SNEP) 1 ended somewhere 2015, it would have been good to use projections from the SNEP 2 but this is still not available. For the purpose of academics and reliability, the study sort to the use of the projection by (Sarkodie, 2017), which is a published academic paper.

The CO₂ emissions of Ghana's commitment to NDC's in relation to power plants were analysed. However, the health and environmental impacts (externalities) of power generation to the population, in particular, has not been analysed.

The study, in addition, did not model the cost of fuels that were used to generate electricity. That notwithstanding, the variable cost related to the fuels has been considered but the fuel cost to power producers in the country has not been considered in the study.

Another substantial limitation of the study is the data used. It was very difficult to acquire data on the existing power plants in the country, especially the investment

cost of the power plants. The modelling processing has also been difficult largely as a result of time and financial constraint.

6.5 Recommendations for future studies.

This study established that the installation of capacity additions and the generation of electricity to satisfy end-users is heavily associated with environmental concerns and economic cost. It is therefore recommended that future studies be conducted into the full cost of fuel options that are needed to supply electricity at a cheaper cost, and availability but in a friendly environment. In addition, electricity demand projections should be made with key attention to government policy on a broad diversification of energy options in Ghana. Finally, the health and environmental impacts (externalities) of power generation to the population in particular should also be analysed.

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APPENDIX 1.

Table 5.1: Least cost installed capacity shares by technology (MW)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|---------|--------|--------|---------|--------|---------|--------|---------|------------|
| 2018 | 36.0424 | 5.4032 | 0.0000 | 58.5518 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2021 | 36.3542 | 5.4499 | 0.0000 | 58.1932 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 100 |
| 2024 | 36.3542 | 5.4499 | 0.0000 | 58.1932 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 100 |
| 2027 | 40.1939 | 6.0256 | 0.0000 | 53.7776 | 0.0000 | 0.0000 | 0.0000 | 0.0029 | 100 |
| 2030 | 44.7467 | 6.6493 | 0.0000 | 48.6008 | 0.0000 | 0.0000 | 0.0000 | 0.0033 | 100 |
| 2033 | 43.7444 | 6.7699 | 0.0000 | 49.4824 | 0.0000 | 0.0000 | 0.0000 | 0.0033 | 100 |
| 2036 | 46.1023 | 7.1316 | 0.0000 | 46.7661 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 48.0141 | 7.3568 | 0.0000 | 44.6291 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 53.0907 | 0.0000 | 0.0000 | 46.9093 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 48.9642 | 6.6327 | 0.0000 | 44.4031 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 48.5945 | 6.5826 | 0.0000 | 44.8229 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.2 HEG Least cost installed capacity shares by technology (MW)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|--------|-------|-------|---------|-------|---------|-------|---------|------------|
| 2018 | 32.611 | 4.889 | 0.000 | 62.498 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2021 | 31.519 | 4.725 | 0.000 | 63.753 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2024 | 31.519 | 4.725 | 0.000 | 63.753 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2027 | 34.366 | 5.152 | 0.000 | 60.480 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2030 | 42.287 | 6.284 | 0.000 | 51.426 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2033 | 41.303 | 6.391 | 0.000 | 52.303 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2036 | 44.385 | 6.596 | 0.000 | 49.020 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2039 | 45.281 | 6.729 | 0.000 | 47.990 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2042 | 47.856 | 0.000 | 0.000 | 52.144 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2045 | 47.155 | 6.388 | 0.000 | 46.458 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2047 | 44.097 | 5.973 | 0.000 | 49.930 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.3: Electricity Generation Shares by Technology (GWh)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Total (%) |
|-------|---------|--------|--------|---------|--------|---------|--------|---------|-----------|
| 2018 | 59.9881 | 3.3536 | 0.0000 | 36.6566 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2021 | 65.2046 | 3.2930 | 0.0000 | 31.5007 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2024 | 64.2631 | 3.2463 | 0.0000 | 32.4889 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2027 | 63.4955 | 3.2081 | 0.0000 | 33.2948 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2030 | 62.4457 | 3.1505 | 0.0000 | 34.4022 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2033 | 61.7219 | 3.1106 | 0.0000 | 35.1659 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2036 | 61.1204 | 3.0757 | 0.0000 | 35.8039 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 66.8601 | 3.0403 | 0.0000 | 30.0996 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 59.9324 | 2.7696 | 0.0000 | 37.2980 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 59.3232 | 0.8264 | 0.0000 | 39.8504 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 58.7887 | 0.8203 | 0.0000 | 40.3910 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.4: HEG Least Cost Electricity Generation Shares by Technology (GWh)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|---------|--------|--------|---------|--------|---------|--------|---------|------------|
| 2018 | 56.0868 | 3.0485 | 0.0000 | 40.8631 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2021 | 59.2800 | 2.9933 | 0.0000 | 37.7251 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2024 | 58.4226 | 2.9509 | 0.0000 | 38.6250 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2027 | 57.7234 | 2.9161 | 0.0000 | 39.3589 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2030 | 57.1274 | 2.8640 | 0.0000 | 40.0071 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2033 | 56.6294 | 2.8278 | 0.0000 | 40.5413 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2036 | 55.7669 | 2.7960 | 0.0000 | 41.4371 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 55.8231 | 2.7639 | 0.0000 | 41.4130 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 54.4854 | 2.5176 | 0.0000 | 42.9970 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 54.4030 | 0.7513 | 0.0000 | 44.8457 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 53.4488 | 0.7457 | 0.0000 | 45.8055 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.5: NDC 15% Least Cost Installed Capacity Shares by Technology (MW)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|---------|--------|--------|---------|--------|---------|--------|---------|------------|
| 2018 | 36.0424 | 5.4032 | 0.0000 | 58.5518 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2021 | 35.3799 | 5.3039 | 2.6798 | 56.6337 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2024 | 35.3799 | 5.3039 | 2.6798 | 56.6337 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2027 | 39.0063 | 5.8475 | 2.9545 | 52.1888 | 0.0000 | 0.0000 | 0.0000 | 0.0028 | 100 |
| 2030 | 43.2798 | 6.4313 | 3.2782 | 47.0075 | 0.0000 | 0.0000 | 0.0000 | 0.0032 | 100 |
| 2033 | 42.5539 | 6.5136 | 3.3202 | 47.6091 | 0.0000 | 0.0000 | 0.0000 | 0.0032 | 100 |
| 2036 | 44.8406 | 6.8606 | 3.3100 | 44.9889 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 44.2298 | 6.7318 | 8.2003 | 40.8381 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 49.3116 | 0.0000 | 8.9261 | 41.7623 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 45.3892 | 6.1484 | 9.1554 | 39.3070 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 45.0714 | 6.1054 | 9.0913 | 39.7319 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.6: HEG NDC 15% Least Cost Installed Capacity Shares by Technology (MW)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|--------|-------|--------|---------|-------|---------|-------|---------|------------|
| 2018 | 32.611 | 4.889 | 0.000 | 62.498 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2021 | 31.431 | 4.712 | 2.433 | 61.422 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2024 | 31.431 | 4.712 | 2.433 | 61.422 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2027 | 33.891 | 5.081 | 3.701 | 57.324 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2030 | 41.543 | 6.173 | 4.606 | 47.675 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2033 | 41.092 | 6.221 | 4.642 | 48.042 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2036 | 41.772 | 6.207 | 7.569 | 44.451 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2039 | 42.500 | 6.315 | 7.701 | 43.483 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2042 | 43.962 | 0.000 | 10.204 | 45.834 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2045 | 41.860 | 5.670 | 10.485 | 41.984 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2047 | 40.527 | 5.490 | 10.152 | 43.831 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.7: NDC 15% Least Cost Electricity Generation Shares by Technology (GWh)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|----------|---------|--------|--------|---------|--------|---------|--------|---------|------------|
| 2018.000 | 50.7992 | 3.3536 | 0.0000 | 45.8455 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2021.000 | 64.1428 | 3.2982 | 5.1108 | 27.4466 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2024.000 | 64.3632 | 3.2514 | 5.0382 | 27.3455 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2027.000 | 63.5108 | 3.2130 | 4.9788 | 28.2958 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2030.000 | 62.3696 | 3.1552 | 4.9275 | 29.5460 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2033.000 | 61.7332 | 3.1151 | 4.8648 | 30.2853 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2036.000 | 64.1061 | 3.0775 | 2.2293 | 30.5871 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039.000 | 65.5620 | 3.0453 | 5.5694 | 25.8233 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042.000 | 60.0959 | 2.7743 | 5.5039 | 31.6259 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045.000 | 59.3037 | 0.8280 | 6.0618 | 33.8065 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047.000 | 58.8984 | 0.8218 | 6.0169 | 34.2629 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.8: HEG NDC 15% Electricity Generation Shares by Technology (GWh)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|---------|--------|--------|---------|--------|---------|--------|---------|------------|
| 2018 | 42.5128 | 3.0485 | 0.0000 | 54.4371 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2021 | 59.5413 | 2.9977 | 4.7462 | 32.7132 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2024 | 58.9184 | 2.9552 | 4.6789 | 33.4460 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2027 | 57.8542 | 2.9212 | 5.5568 | 33.6664 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2030 | 57.0715 | 2.8690 | 5.5487 | 34.5094 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2033 | 56.5402 | 2.8325 | 5.4782 | 35.1476 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 100 |
| 2036 | 55.7838 | 2.8002 | 5.1266 | 36.2894 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 56.3041 | 2.7681 | 5.0678 | 35.8600 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 54.5775 | 2.5226 | 6.4169 | 36.4829 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 54.3384 | 0.7529 | 6.8451 | 38.0637 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 53.5894 | 0.7473 | 6.7943 | 38.8690 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.9: NDC 30% Least cost installed capacity shares by technology (MW)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|---------|--------|---------|---------|--------|---------|--------|---------|------------|
| 2018 | 36.0424 | 5.4032 | 0.0000 | 58.5518 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2021 | 35.3593 | 5.3008 | 2.7366 | 56.6007 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2024 | 32.6055 | 4.8880 | 10.3117 | 52.1925 | 0.0000 | 0.0000 | 0.0000 | 0.0024 | 100 |
| 2027 | 35.6608 | 5.3460 | 11.2779 | 47.7126 | 0.0000 | 0.0000 | 0.0000 | 0.0026 | 100 |
| 2030 | 39.1994 | 5.8250 | 12.3970 | 42.5757 | 0.0000 | 0.0000 | 0.0000 | 0.0029 | 100 |
| 2033 | 38.4547 | 5.8963 | 12.5489 | 43.0972 | 0.0000 | 0.0000 | 0.0000 | 0.0029 | 100 |
| 2036 | 37.9664 | 5.8214 | 18.0380 | 38.1743 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 38.9582 | 5.9002 | 19.3489 | 35.7927 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 44.0107 | 0.0000 | 21.4470 | 34.5423 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 40.5002 | 5.4862 | 21.6768 | 32.3369 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 40.1384 | 5.4371 | 21.8212 | 32.6032 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.10: HEG NDC 30% Least cost installed capacity shares by technology (MW)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|--------|-------|--------|---------|-------|---------|-------|---------|------------|
| 2018 | 32.611 | 4.889 | 0.000 | 62.498 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2021 | 31.841 | 4.773 | 2.464 | 60.918 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2024 | 28.607 | 4.289 | 12.371 | 54.731 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2027 | 30.933 | 4.637 | 13.376 | 51.052 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2030 | 37.206 | 5.529 | 16.089 | 41.173 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2033 | 36.409 | 5.599 | 16.294 | 41.696 | 0.000 | 0.000 | 0.000 | 0.003 | 100 |
| 2036 | 36.850 | 5.487 | 20.922 | 36.741 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2039 | 37.041 | 5.504 | 22.819 | 34.635 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2042 | 38.747 | 0.000 | 23.870 | 37.383 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2045 | 36.182 | 4.901 | 24.212 | 34.705 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2047 | 35.697 | 4.836 | 23.887 | 35.580 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.11: NDC 30% Least Cost Electricity Generation Shares by Technology (GWh)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|---------|--------|---------|---------|--------|---------|--------|---------|------------|
| 2018 | 18.0138 | 3.3544 | 0.0000 | 78.6301 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2021 | 72.1276 | 3.2983 | 5.2221 | 19.3503 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2024 | 63.8199 | 3.2593 | 12.9649 | 19.9541 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2027 | 63.9028 | 3.2208 | 12.8116 | 20.0631 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2030 | 63.1936 | 3.1628 | 12.6792 | 20.9627 | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 100 |
| 2033 | 63.1140 | 3.1223 | 12.5171 | 21.2449 | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 100 |
| 2036 | 60.9610 | 3.0885 | 14.3679 | 21.5825 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2039 | 63.4647 | 3.0537 | 15.0349 | 18.4466 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2042 | 60.2901 | 2.7823 | 14.8598 | 22.0678 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2045 | 59.4292 | 0.8305 | 16.1349 | 23.6053 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |
| 2047 | 58.9736 | 0.8244 | 16.2683 | 23.9336 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 100 |

Source: Author's estimation using MESSAGE model, 2018

Table 5.12: HEG NDC 30% Least Cost Electricity Generation Shares by Technology (GWh)

| Years | Hydro | Solar | Wind | Thermal | Coal | Nuclear | Tidal | Biomass | Totals (%) |
|-------|--------|-------|--------|---------|-------|---------|-------|---------|------------|
| 2018 | 16.158 | 3.049 | 0.000 | 80.791 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2021 | 69.173 | 2.998 | 4.746 | 23.082 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2024 | 58.188 | 2.965 | 15.247 | 23.599 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2027 | 58.317 | 2.930 | 15.066 | 23.686 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2030 | 57.691 | 2.877 | 14.912 | 24.519 | 0.000 | 0.000 | 0.000 | 0.002 | 100 |
| 2033 | 57.757 | 2.841 | 14.722 | 24.679 | 0.000 | 0.000 | 0.000 | 0.001 | 100 |
| 2036 | 55.929 | 2.809 | 16.081 | 25.180 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2039 | 54.718 | 2.778 | 17.292 | 25.211 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2042 | 54.873 | 2.531 | 17.088 | 25.507 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2045 | 54.267 | 0.756 | 18.351 | 26.626 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |
| 2047 | 53.826 | 0.750 | 18.214 | 27.210 | 0.000 | 0.000 | 0.000 | 0.000 | 100 |

Source: Author's estimation using MESSAGE model, 2018