

NHH



Developing an Optimal Energy Mix: Eradication of Periodic Power Crisis In Ghana till 2030

Ishmael Nii Adumoah Oku

Roy Tan

Supervisor: Gunnar Eskeland

Master's Thesis in Energy Natural Resource and Environment

NORWEGIAN SCHOOL OF ECONOMICS

This thesis was written as a part of the Master of Science in Economics and Business Administration at NHH. Please note that neither the institution nor the examiners are responsible – through the approval of this thesis – for the theories and methods used, or results

Executive Summary

The present situation in Ghana presents major challenges in providing the required energy in a reliable and sustainable manner considering environmental and economic impacts of energy production and use and the nexus between energy and development. Despite having no lack of endowment with varied natural resources, some with significant potential, Ghana has had several energy crises in the past four decades and is currently in the midst of one.

The Strategic National Energy Planning Authority formulated a comprehensive plan for the development, utilization and efficient management of energy resources available to the country and has defined a target basket of energy mix to flexibly avail production to keep up with the country's general trend of an expanding economy, growing population and the country's energy question.

This paper presents some historical energy use patterns in Ghana, an overview of the relevant governmental bodies and policies that were put in place to define the future energy scenery with the main objective of proposing an 'optimal' course of action towards practical execution of energy project mix in line with the national's strategic targets and plans capable of supplying the annual electrical energy needs of Ghana in order to eradicate periodic power crisis in Ghana from 2016 till 2030 (given Ghana's current endowments). Using a linear optimization model, this thesis also seeks to provide an optimal energy mix with an optimal year-on-year energy resource development path that will ensure growing annual energy demand is met with the least economic impact. The paper does this by considering generation from various energy sources, such as gas, nuclear, hydro, wind and solar photovoltaic in keeping up with the strategic renewable mix (excluding large hydro and nuclear) of 10% of installed capacity from 2020 onwards.

Contents

Executive Summary	i
List of Tables	vi
List of Figures.....	vii
1 Introduction.....	1
1.1 Motivational background	1
1.2 Aim of thesis	2
1.3 Choice of assessment methodology	3
1.4 Structure of the Thesis.....	3
1.5 Terminology	4
1.6 Abbreviation.....	6
2 Electricity, Energy Policy and Energy Resources in Ghana.....	7
2.1 Institutional framework of the Power Sector of Ghana.....	7
2.2 Chronology of Electric Power Generation in Ghana	10
2.2.1 Before Akosombo	10
2.2.2 Hydro Years	10
2.2.3 Thermal Complementation	11
2.2.4 Current Electricity Generation Situation	12
2.3 Power Crisis in Ghana.....	14
2.4 Major Factors Accounting for Periodic Power Crisis in Ghana.....	15
2.4.1 Finance.....	16
2.4.2 Limited Rainfall Resulting in Low Water Volumes	17
2.4.3 Population growth, industrialization and urbanization	18
2.5 Energy policy and resource potential of Ghana	20

2.5.1	Overview of Policies in the Ghanaian Energy Sector.....	20
2.5.1.1	Strategic National Energy Policy (SNEP).....	21
2.5.1.2	National Energy Policy/Energy Sector Strategy and Development Plan	23
2.5.1.3	Renewable Energy Act, 2011	24
2.5.1.4	Ghana Shared Growth and Development Agenda II.....	24
2.5.1.5	Country Action Plan for Sustainable Energy for All (SE4All)	26
2.5.2	Energy resource potential of Ghana.....	26
2.5.2.1	Solar Energy Resource	27
2.5.2.2	Wind Energy Resource.....	29
2.5.2.3	Hydro Energy Resource.....	32
2.5.2.4	Biomass Energy Resource.....	33
2.5.2.5	Petroleum.....	34
3	Theoretical Perspectives.....	37
3.1	Energy Economics.....	37
3.1.1	Real Option Analysis	38
3.1.2	Net Present Value (NPV).....	39
3.1.3	Levelized cost of Energy (LCOE)	40
3.2	Linear Optimization	42
3.2.1	Assumptions under linear optimization	43
3.2.2	Linear Optimization Problem Formulation.....	44
3.2.3	Solution Methods	45
3.3	Literature Review and Related Works	46
4	Methodology	49
4.1	Energy Source Selection	51
4.2	Installed Capacities	51

4.3	Parameters	52
4.3.1	Hydro	52
4.3.2	Thermal (Gas & Oil).....	52
4.3.3	LCOE parameters.....	53
4.3.4	Demand and Year-on-year Demand Growth	56
4.4	Electricity Supply Expansion Plan.....	58
4.5	Model definition.....	58
5	Results and Discussions	62
5.1	Optimal Mix	62
5.2	Resource development plan	64
5.3	Sensitivity Analysis.....	67
5.4	Meeting the Optimal Energy Mix	72
5.4.1	Hydro	72
5.4.2	Solar	72
5.4.3	Thermal (Oil and Gas)	73
5.4.4	Wind.....	73
6	Conclusion and Recommendations	74
6.1	Conclusion.....	74
6.2	Recommendations	75
7	Bibliography	76
8	Appendix I	79
8.1	Model – Scenario 1 (Expansion plan option 2).....	79
8.2	Data	80
8.3	Model – Scenario 2	81
8.4	Data	81

8.5	LCOE Calculator – Model	82
8.6	LCOE Calculator – Data	83

List of Tables

Table 1 Key institutions in the Power Sector of Ghana.....	9
Table 2 Electricity generation facilities and respective installed and dependable capacities –June 2016.....	13
Table 3 Solar energy related statistics in Ghana.....	29
Table 4 Installed Generation Capacity (MW) as at 31 December 2015.....	51
Table 5 Summary of Energy Supply Parameters.....	56
Table 6 Growth projections - Ghana.....	56
Table 7 Optimal Energy Mix - Target generation capacity	62
Table 8 Optimal Energy Mix (2016 - 2030)	63
Table 9 Resource development plan for Optimal Energy Mix	65
Table 10 Resource development cost (\$m/MW)	66
Table 11 LCOE values of energy sources at various rates	68
Table 12 Resource capacity plan in a stressed environment (High interest rate coupled with high fuel cost).....	69
Table 13 Resource Development Path - Stressed Scenario 2016 - 2030.....	71

List of Figures

Figure 1 Key players in the Energy Sector of Ghana's economy	8
Figure 2 Dependable electricity generation capacity in Ghana (July, 2016).....	12
Figure 3 Water levels in the Volta Lake reservoir	17
Figure 4 Electricity consumption according to consumer classification (2006 - 2014)	19
Figure 5 Trends in Primary Energy Supply in Ghana.....	20
Figure 6 Global Solar Irradiation in Ghana	27
Figure 7 Ghana's annual average total daily sum of GHI in Wh/m ² /day (3-years average).....	28
Figure 8 Wind energy resource map of Ghana (wind speed at 50 m height)	30
Figure 9 Ghana - Wind Electric Potential.....	31
Figure 10 Distribution of small and medium hydro resources in Ghana.....	32
Figure 11 Offshore activity map of Ghana's petroleum exploration industry	34
Figure 12 List of discoveries and their state	35
Figure 13 Electricity consumption per capita for South Africa, China, Brazil, India and Ghana	57
Figure 14 Optimal Energy Mix - 5 year growth starting from 2020 with 2016 as base.....	64
Figure 15 Energy Source LCOE sensitivity to discount rates	68
Figure 16 Comparative view of Optimal Energy Mix and Energy Mix in stressed environment (2020, 2025 and 2030)	70

1 Introduction

To aid structure our thesis, we present the background motivation for the choice of topic. We will also provide a brief description of the structure and aims of our thesis.

1.1 Motivational background

Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive. Development is not possible without energy, and sustainable development is not possible without sustainable energy (The Secretary-General's High-Level Group on Sustainable Energy for All, 2012).

According to the technical support unit working group III of the IPCC, there exist three major global energy challenges; (a) ensuring sufficient energy supply to meet growing energy demand, (b) curbing the contribution of the energy supplied to climate change, and (c) providing everybody with access to energy services (IPCC, 2011). Ensuring sufficient energy supply requires the provision of more energy infrastructure which implies increased levels of associated costs and attendant complexities associated with such provisions (Verbong and Geels, 2010). Additionally, increasing global energy demand, in the current fossil fuel dominated global energy source, indicates likely increasing levels of ambient pollution with its attendant effects, *ceteris paribus*.

To maintain pace with the growing energy demand, countries will need to adjust to changing circumstances in energy provision, both globally and nationally, regarding social, economic and resource concerns as well as improving efficiency in consumption. Impliedly, a country's energy history and profile becomes a major factor in deciding its energy mix on the path to meeting its energy challenges.

In most African nations, achieving continued and sustainable energy provision has proved difficult over the years. Mostly, this difficulty has been due to the huge financial investments required for the provision of the needed energy (Brunnschweiler, 2010). Most of these countries become reliant on energy sources immediately available with limited exploration and investment into other probable sources until a crisis results.

In Ghana, a developing country, energy shortfalls, occasioned by varied factors, that lead to power crisis have been periodically experienced over the past four decades. Despite supply improvement, assessments undertaken in a bid to improve electricity supply during and after these crises, efforts at meeting the changing dynamics of energy generation and growing demand have been inadequate. Additionally, despite the availability of literature on the crisis situation, energy resource profile and history of Ghana and suggestions of energy resources that could be exploited, not much exists on optimal sustainable energy mix options with an annual supply growth projection that has the capability of eradicating the periodic power crisis the country faces.

1.2 Aim of thesis

The aim of this thesis is to assess which energy sources, per the current energy profile, history and policies of Ghana, could be sustainably developed with the least likely economic impact (least financial investment commitment) to ensure the sustainable and continuous supply of electricity in Ghana. Additionally, the thesis seeks to add to available energy planning literature and research, especially for Ghana, in a bid to aid further research into Ghana's sustainable energy provision beyond 2030. We will try to answer the following questions;

- i. Which energy sources, when developed, could afford the least economic impact while ensuring the continuous supply of electrical energy in Ghana?
- ii. At what rate should the optimal choice of energy sources be developed, over the years, to ensure that growing demand for electrical energy is met year after year till 2030

1.3 Choice of assessment methodology

Our thesis focusses on an economic optimization path in seeking to provide an optimal energy mix option year on year till 2030. This is influenced by the choice of LCOE as the economic measure for optimization. Vidal-Amaro et al., 2015, notes that “When optimizing from a techno-operational standpoint, common criteria’s are reserve/backup capacity requirements, import and export dependence, Primary Energy Consumption (PEC) and fuel savings, Renewables shares, carbon dioxide emissions and Excess Electricity Production (EEP) while, economic optimization utilizes societal costs or cost-benefit data, utility costs, rate impact, levelized cost of energy or levelized unit electricity costs, total resources spent by consumers, energy companies and government bodies, and marginal costs”.

Additionally, this thesis uses linear optimization as the choice of optimization method owing to its ease of use and the suitability of its proportionality, divisibility and additivity properties towards the objectives of this thesis. These properties serve the requirements for power supply in terms of additivity (irrespective of the source), divisibility (once demand is met, any excesses may serve as backup/reserve supply) and proportionality of supply from the various sources.

1.4 Structure of the Thesis

Chapter 2 discusses electricity, energy policy and energy resources in Ghana. We delve into the history of electricity in Ghana, the current state of generation and the major factors contributing to the Ghana’s power crisis. We further discuss policies, strategies and plans in Ghana’s energy sector and close the chapter with a discussion on energy profile and potential in Ghana.

In Chapter 3, we present theoretical perspectives and literature review on some of the central theories relating to energy mix optimization.

Chapter 4 presents an overview of the methods applied, including the procedures, assumptions and data used for the study. Discussions on data in Chapter 4 covers the demand and supply parameters of electricity generation and demand in Ghana. Additionally, based on deductions from theories in Chapter 3, we develop a linear optimization model that takes cognizance of the peculiar resource potential and energy challenges of Ghana.

In Chapter 5, we present our results and discuss these results in line with the objectives of our thesis. We undertake sensitivity analysis of a few parameters and discuss the observations made. We further discuss the optimal energy mix and development path of the energy sources.

In Chapter 6, we conclude offer potential recommendations for future research.

1.5 Terminology

Agro	Cultivated mixtures of agriculture products
Capacity Factor	The net capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time.
Capacity Recovery Factor	A capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time
Dependable capacity	The dependable capacity of a generating facility is a fluctuating value that depends upon the capability of the system to deliver that energy at a given moment
Dispatch	Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators or of the plant owner; that is, generating plants that can be turned on or off, or can adjust their power output accordingly to an order.
Distribution generation	Power generation at the point of consumption
Installed capacity	Production capacity of plant based either on its rated (nameplate) capacity
Intermittency	An intermittent energy source is any source of energy or electrical power that is not continuously available due to some factor outside direct control

Joules	The work required to produce one watt of power for one second
Levelization Factor	The levelization factor converts the total capital value to a uniform annual amount (also called an annuity)
Load Shedding	The deliberate shutdown of electric power in a part or parts of a power-distribution system, generally to prevent the failure of the entire system when the demand strains the capacity of the system
Wind Class	Three dimensions — wind speed, extreme gusts, and turbulence — encompass the wind class of a wind turbine

1.6 Abbreviation

\$m/MW	Million Dollars per Megawatt
API	American Petroleum Institute gravity metric
BCF	Billion Cubic Feet
EC	Energy Commission
EPP	Excess Electricity Production
GHI	Global Horizontal Irradiance
GOG	Government of Ghana
GWH	Gigawatt
Hydro_Ako	Hydro power generation from Akosombo and Kpong dams
Hydro_Bui	Hydro power generation from Bui dam
Hydro_mini	Hydro power generation from small/mini dams
IPP	Independent Power Producer
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MCF	Million Cubic Feet
MMBtu	One Million British Thermal Units
MTOE	Million Tonnes of Oil Equivalent
MW	Megawatt
MWH	Megawatt hours
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PURC	Public Utilities Regulatory Commission
PV	Photovoltaic
SNEP	Strategic National Energy Plan
TOE	Tonne of Oil Equivalent
VRA	Volta River Authority
Wind 3	Wind power from Wind Class 3 resources of 7 m/s average wind speed
Wind 4	Wind power from Wind Class 4 resources of 7.5 m/s average wind speed
Wind 5	Wind power from Wind Class 5 resources of 8 m/s average wind speed
Wind 6	Wind power from Wind Class 6 resources of 8.8 m/s average wind speed

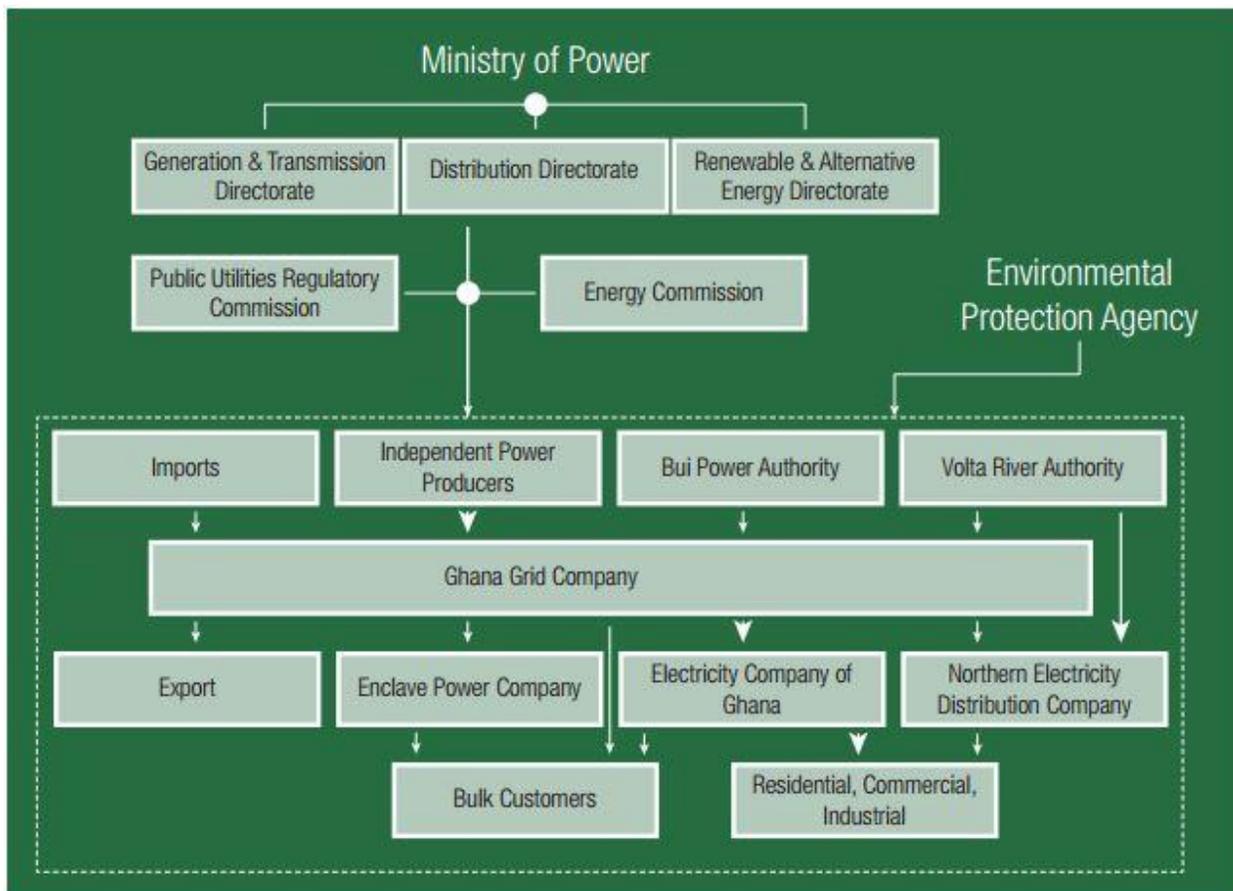
2 Electricity, Energy Policy and Energy Resources in Ghana

Ghana's electrical energy generation and supply has been reliant on hydropower for decades. For three out of the past five decades, inexpensive hydropower was the main electricity supply source for meeting electrical energy demand in Ghana. Ghana, as a developing country, has had relatively low electrical energy demand despite continuously increasing demand as a result of population growth, gradual urbanization and industrialization of various sectors of the economy (Gyamfi et al., 2015). However, demand has periodically outmatched supply, resulting in periodic electricity supply crisis.

2.1 Institutional framework of the Power Sector of Ghana

Government of Ghana (GoG), in 1994, launched the nation's Power Sector Reforms (PSR) in a bid to "...enhance transparency in the regulation of the sector and to open up the industry to private sector participation by dismantling the vertically integrated utility structure and availing the generation and distribution aspects of the industry to market competition" (Ministry of Power, 2015). These reforms has resulted in the unbundling of the sector that ensures the operational functions of the power supply chain, generation, transmission and distribution, are well segregated for better performance and management (Ministry of Power, 2015).

The parliament of Ghana, by law enactment, has established a number of institutions to ensure the proper functioning of the energy sector, and to create a conducive environment for protecting and enhancing private investment in the sector. These agencies are the Energy Commission, PURC and the National Petroleum Authority. The Energy Commission advises government on energy policy and strategy. It is also involved in indicative planning of energy and electricity system expansion and licensing energy sector operators. Established in 1997, PURC is the prime body for setting tariffs and framing customer service regulations. The National Petroleum Authority is an independent regulator which reviews world market price developments, the prices of imported finished products and the operations of Ghana's oil refinery (Energy Commission - Ghana, 2006; International Renewable Energy Agency, 2015). Figure 1 below shows the key institutional players in the power sector of Ghana.



Source: Extract from SREP –Ghana Investment Plan (Ministry of Power, 2015)

Figure 1 Key players in the Energy Sector of Ghana's economy

Though not depicted in Figure 1, the sector also has several active non-governmental organizations (NGOs), research institutes and universities as well as industry associations involved in a range of activities. These activities include renewable energy promotion, research and deployment (International Renewable Energy Agency, 2015). Table 1 lists the institutional players and parties with some level of influence in the sector and briefly describes their respective functions.

Table 1 Key institutions in the Power Sector of Ghana

Institutions	Functions
Association of Ghana Solar Industries (GSI)	Promotes and raises the profile of the solar industry, improves quality, develops standards and arranges renewable energy training
Bulk Oil Storage and Transportation Company (BOST)	Planning for laying and managing strategic petroleum product stocks
CEESD	Dedicated to technologies that offer engineering solutions to
Council for Scientific and Industrial Research (CSIR)	Pursues the implementation of government policies on scientific research and development
Electricity Company of Ghana	Distribution of electricity in southern Ghana
Energy Commission (EC)	Licenses, regulates and monitors energy service providers, develops indicative national energy plans and advises the
Energy Foundation	Promotes energy efficiency/conservation measures and
Environmental Protection Agency (EPA)	Distributes, monitors and enforces environmental policies, including the energy sector
Ghana Investment Promotion Centre	Encourages and promotes investments in Ghana, providing for the creation of an attractive incentive framework and a transparent, predictable and facilitating environment for investment
Ghana National Petroleum Corporation (GNPC)	Oil and gas exploration
GRIDCo	Electricity transmission services
KITE	Energy policy studies and analysis/clean energy enterprise
Ministry of Power (MoP)	Formulates, implements, monitors and evaluates power sector
National Petroleum Authority (NPA)	Regulates, oversees and monitors activities in the downstream petroleum industry
New Energy	Develops and implements clean energy initiatives
Northern Electricity Department	Distribution of electricity in northern Ghana
Oil Marketing Companies (OMCs)	Distribution and marketing of petroleum products
Petroleum Commission (PC)	Regulates and manages the utilization of petroleum resources, and co-ordinates policies on petroleum resources
Public Utilities Regulatory Commission	Regulates tariffs and enforcement of customer service obligations of all public utilities and IPPs
Tema Oil Refinery (TOR)	Crude oil and petroleum product import, crude oil refining and bulk sale of petroleum products to OMCs and bulk consumers
The Energy Center, KNUST	Carries out research, development, demonstration and educational activities in energy technology, policy and management
University of Energy and Natural Resources (UENR)	Provides training in science, technology and management of energy and natural resources
Volta River Authority (VRA)	Generation and transmission of electricity

2.2 Chronology of Electric Power Generation in Ghana

Electrical power generation in Ghana can be catalogued into three main periods. The first period, “*before Akosombo*”, refers to the period prior to the building of Ghana’s main hydropower plant; the Akosombo hydro-power plant. The second period, “*hydro years*”, also refers to the period from 1966 to the mid-eighties. The period marks the years prior to the significant addition of other energy mix options to the hydro power option in a bid to meet rising energy demands. The third period, “*thermal complementation*”, marks the years from the mid-eighties till date. This marks the period from when thermal plants were introduced into Ghana’s electrical energy supply pool till date (Resource Centre for Energy Economics and Regulation, Legon, 2005).

2.2.1 Before Akosombo

In 1914, the first public supply of electricity was undertaken in Ghana. The Gold Coast Railway Administration (GCRA), a national railway company, operated the system; this was used mainly for operating the railway system. Prior to the construction of Akosombo, power generation and supply in Ghana was undertaken using isolated diesel generators dispersed across the country. These generation units were mainly owned by institutions like mines, factories and hospitals. One of such systems was that administered by the GCRA (Resource Centre for Energy Economics and Regulation, Legon, 2005; Kemausuor et al., 2011). Various electricity generation stations were installed across the country during this period and a transmission network gradually started taking shape. Electricity supply during this period was rather unreliable and inadequate. Additionally, owing to the dispersed generation of power, an accurate estimate of demand is not available. However, as the Resource Centre for Energy Economics and Regulation, Legon (2005) puts it, “Total recorded power demand of about 70 MW with the first switch on of the Akosombo station can be used as a proxy for the level of electricity demand in the country just prior to the construction of Akosombo”.

2.2.2 Hydro Years

The hydro years marks the beginning to massive centralized generation and distribution of electricity in Ghana. This was mainly influenced by the desire to develop Ghana’s huge bauxite reserves; an energy intensive act that required a stable continuous source of energy supply. The

first phase of the Akosombo hydro-power dam, consisting of four generating units with an installed capacity of 588 MW, was completed in 1965. Available data indicates that, as of 1967, domestic electricity consumption was less than 20% of installed capacity; 540 GWh (Resource Centre for Energy Economics and Regulation, Legon, 2005). The major industrial consumer of electricity then was Volta Aluminum Company (VALCO); an aluminum smelting company set up to exploit the bauxite resources in Ghana. In 1972, two additional generation units were added to augment the installed capacity to 912 MW. That same year, Ghana commenced the exportation of electricity to neighboring countries like Togo owing to excess supply in the face of a low demand. However, demand doubled to 1300 GWh by 1976 and rose at a rate of 10% per annum thereafter. In 1982, a second hydro-power plant, the Kpong Hydroelectric Power plant was commissioned to add another 160 MW to installed capacity.

2.2.3 Thermal Complementation

With growing local energy demand in the face of fixed hydroelectric power supply, Ghana had its first major electricity supply crisis in 1983, following a severe draught that rendered the hydro dams incapable of supplying the needed electrical energy to meet demand. The draught and resulting supply shortage and its impact necessitated the provision of complementary generation options. Studies carried out indicated that there was a need for developing thermal generation options to complement the all hydro option being exploited (Resource Centre for Energy Economics and Regulation, Legon, 2005). The first 110 MW combustion turbine plant was commissioned in 1997 with a second one in 1998. By 1999, total installed thermal power generation was 330 MW. Subsequent to these, several thermal generations units and additional hydroelectric dam (Bui hydroelectric dam) have been added to Ghana's electricity generation options with the aim of meeting demand and ensuring supply surety. The period from 1997 is noted to be the commencement of introduction of thermal generation options in Ghana not necessarily because that marks the first thermal power generation in Ghana but mainly as a result of the public provision of the said power and the scale at which they were introduced. It is instructive to note that, prior to these, dispersed generation of electricity had been undertaken in the country by means of diesel generators; though with very limited power output and for specific institutional needs.

2.2.4 Current Electricity Generation Situation

With the growing introduction of other energy options into the electricity generation mix of Ghana, thermal generation has gradually overtaken hydroelectric power to become the main supply source for electricity in Ghana. Thermal generation currently constitutes 63% of Ghana's dependable generation capacity with hydroelectric generation constituting 36% of dependable

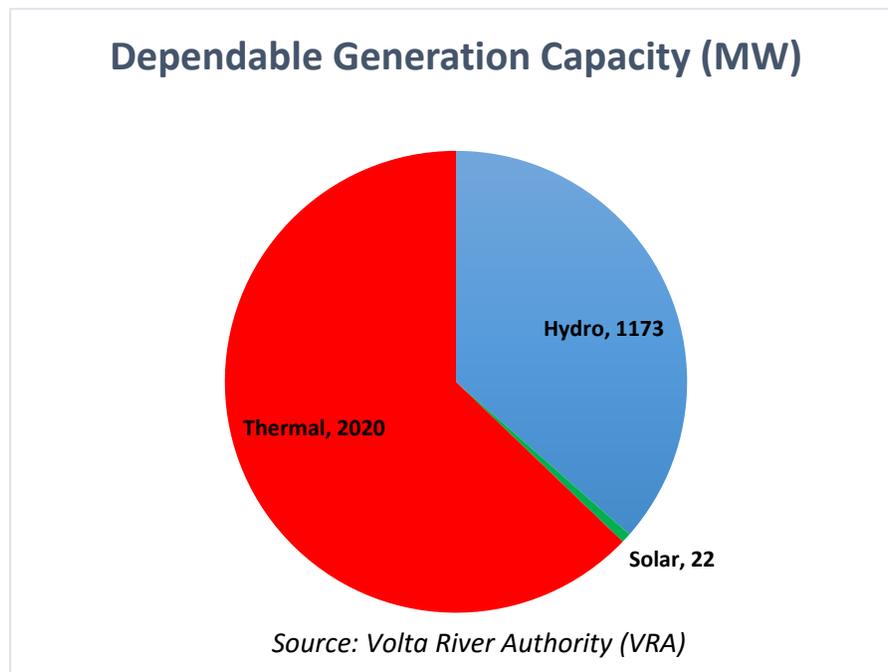


Figure 2 Dependable electricity generation capacity in Ghana (July, 2016)

generation capacity. Solar power takes up the remaining 1%.

Figure 2 above depicts Ghana's dependable electricity generation capacity. Total dependable capacity currently stands at 3,215 MW. Installed capacity, in Table 2 below, however stands at 3,877 MW.

Table 2 Electricity generation facilities and respective installed and dependable capacities –June 2016

Generation Facility	Installed Capacity (MW)	Dependable Capacity (MW)
Akosombo Generation Station	1,020	900
Kpong Generation Station	160	140
Bui Hydroelectric Generation Station	400	133
Takoradi Thermal Power Station (T1)	330	300
Takoradi International Company (TICO/ T2)	330	300
Tema Thermal 1 Power Plant	80	40
Tema Thermal 2 Power Plant	110	100
Tema Thermal 3 Power Plant	80	70
Sunon Asogli Power Plant	550	480
Cenit Energy Thermal Power Plant	110	100
Ameri Thermal Power Plant	250	230
Karpowership Thermal Power Plant	225	200
Kpone Thermal Power Station	210	200
Navrongo Solar Power Plant	2	2
Gomoa Onyandze Solar Power Plant	20	20
Total	3,877	3,215

Source: VRA – Tema Thermal Plant, Station 3

Table 2 above captures electricity generation facilities in Ghana with their respective installed and dependable capacities. Between the installed generation capacity and dependable generation capacity exists a 17% difference. Fortunately, Ghana’s peak load on transmission grid (local demand plus exports) has been stated as 2,118 MW (Energy Commission - Ghana, 2016). Despite the excess supply capacity over peak load demand, Ghana hasn’t been able to meet electricity demand over a period of time.

Though many reasons have been given for the inadequate supply of power, two major issues have stood out as main drivers; low volumes of water for hydropower generation and the lack of fuel for thermal power generation. Successive governments have sought to improve power generation through efforts at improving the availability of fuel for generators whiles creating the necessary environment for the introduction of other mix options; mainly renewable options with an exceptional mention of nuclear energy as a long term option to ensure supply stability.

2.3 Power Crisis in Ghana

The first major electricity crisis in Ghana occurred in 1983 following a severe draught. Recorded rainfall within the catchment area of the Akosombo hydropower dam, from 1983 to 1985 was very low, resulting in inadequate water volumes for power production. Meanwhile, demand had been growing over years with no changes in supply. Additionally, as a result of a contractual requirement, 370 MW of the power generated had to be supplied to VALCO. This effectively reduced the power available for domestic consumption; hence the crisis. The government, in a bid to reduce the impact of the crisis on the economy and the population at large, renegotiated VALCO's contractual demand from 370 MW to 20 MW. Additionally, supply for domestic consumption was curtailed. Studies undertaken in order to improve the situation also indicated the need for the introduction of thermal generation options to augment the hydropower resources.

Between 1997 and 1999, Ghana had 330 MW of thermal generation capacity added to the available hydropower generation capacity. Additionally, Ghana signed an agreement in 1995 for the development of the West African Gas Pipeline (WAGP); a project that sought among other things to distribute LNG from Nigeria to the agreeing parties – Nigeria, Togo, Benin and Ghana. Meanwhile, owing to improved electricity access in the country, domestic electricity consumption was rising at about 10% per annum. According to Kemausuor et al. (2011), domestic electricity consumption grew at an annual rate to 9.4%, between 1990 and 2001, from 4,457 GWh to 6,033 GWh (consumption from VALCO excluded). They attribute this growth to an "...impressive increase in electricity access from 28% in 1988, 32% in 1992 and 43.7% in 2000".

Between 1998 and 2000, Ghana suffered its second major power crisis despite the introduction of thermal options from 1997. The impact of climate change on rainfall patterns in the Sub-Saharan Africa region coupled with delayed and inadequate investment in alternate power generation options led to inadequate supply in the face of growing demand. Ghana commenced power rationing and load shedding in an attempt at ameliorating the adverse impact of the shortages. Additionally, the government imported power from la Cote d'Ivoire and also renegotiated VALCO's demand from 245 MW to 20 MW. Other thermal sources, including diesel generation plants, were either contracted or introduced to help improve the power situation.

Ghana suffered a third power crisis by 2006. This persisted till 2007 with poor rainfall and inadequate thermal generation as the main drive factors. In response to this, the government purchased VALCO and in effect freed 370 MW for use by other sectors of the economy. Additionally, other thermal generating plants (a mine reserve plant with a 80 MW capacity and a 25 MW diesel generation unit) were engaged to help deal with the situation. Also, numerous power projects were commenced in the hope of forestalling a future recurrence. These include the Kpong Thermal Power Plant, Bui Hydro Power Plant, Takoradi Thermal Station 1, TICO /T2, Tema Thermal Power Plant, Sunon Asogli Power Plant and CENIT Energy Thermal Plant. Some of these power plants were IPP plants with power purchasing agreements.

Ghana's fourth and most current power crisis commenced in 2012 and is yet to be fully resolved as of July 2016. As in all the previous power crisis situations, low rainfall within the catchment area of Ghana's hydropower dams have led to prolonged periods of low water volumes for hydropower generation. Additionally, rising demand coupled with financial challenges in the power generation sector of the economy have been independently cited as contributing factors to the incidence of power shortage in the country.

2.4 Major Factors Accounting for Periodic Power Crisis in Ghana

Despite the repeated mention of low water volumes as precursors to the periodic energy crises in Ghana, researchers have argued that Ghana's energy crisis is largely due to shortage in generation capacity and not necessarily a water problem (Brew-Hammond and Kemausuor, 2007). This argument may well be justified on the premises that other power generation options like thermal, nuclear and other forms of renewable energy have existed and been available for exploitation throughout the periods of the recurring crisis. A number of issues have been identified as underlying factors for these crisis. These include finance, limited rainfall, and population growth, urbanization and industrialization.

2.4.1 Finance

Finance is arguably the biggest factor leading to the current periodic power crisis in Ghana. Most other factors can largely be traced back to the lack of funds. These factors include gas and fuel supply challenges and credit worthiness of the main power off-takers and distributor in Ghana. However, the financing challenges are pivoted on three main issues; VRA's financial challenges, creditworthiness of off-takers and below cost-recovery electricity tariffs.

The Ministry of Petroleum (2016), notes that, "The Volta River Authority (VRA), Ghana's state owned power generation company, is facing major financial difficulties and is not in a position to raise capital for major investments in power generation. Shortages in gas supply have meant that VRA having to rely on expensive light crude oil in its thermal power generation facilities. Without adequate electricity tariff increases, the World Bank projects that VRA is facing imminent financial collapse.

The two state owned wholesale electricity purchasers, the Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCo) are in financial difficulties, bringing their creditworthiness as off takers of electricity into question. This detracts potential independent power producers (IPP) from investing in the sector. Besides low electricity tariffs, the main reasons for the financial difficulties are high technical and non-technical losses and arrears from public sector consumers. A major reform programme is currently underway at ECG aiming to reduce losses, increase productivity of the workforce by introducing performance based pay, and streamlining decision-making processes through a new management structure.

Electricity tariffs for the past few years have been below cost recovery levels resulting, among other things, in the financial difficulties of NEDCo and ECG. More importantly, however, this has sent a negative signal to potential market entrants, the independent power producers about the viability of investments in power generation".

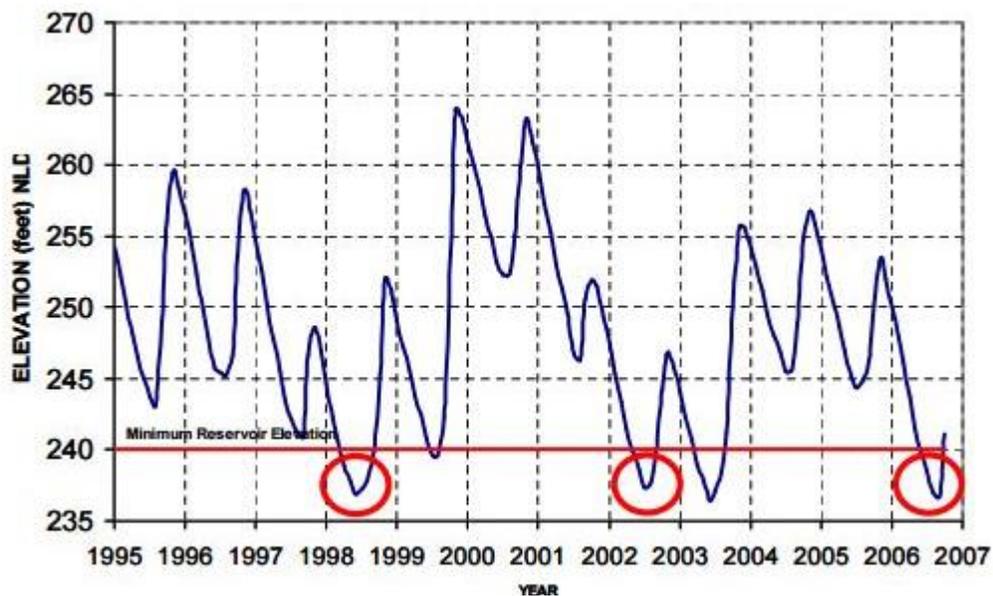
Meanwhile, the local debt stock within the energy sector has been reported as a threat to the local banking industry. As of July, 2016, the Volta River Authority (VRA), owed local banks a cumulative amount of over \$ 1 billion; leading to reluctance on the part of the banks in advancing further credit to the VRA for the purposes of buying fuel (Quist, 2016).

The VRA’s financial problems have largely been attributed to financial problems and inefficiencies from the nation’s dominant power distributor, the electricity company of Ghana (ECG); distributing about 90% of all generated power. The ECG is considered a high risk entity owing to a poor credit performance over the years.

ECG’s financial situation has been cited as difficult with losses being recorded in multiple years. As Mathrani et al. (2013) puts it, “ECG does not have the ability to finance these investments. ECG is in a difficult financial situation today, as it often has been in the past.”

Additionally, lack of interconnection of fuel supply lines (gas pipelines) between generation plants results in idleness of some thermal plants over long periods of time. Typically, Ghana’s own gas production fields are only able to supply gas to thermal plants within their vicinity owing to the lack of connectivity between other generation stations and the gas fields. Discussions surrounding laying connecting pipelines usually point to the same financing problem as the main challenge.

2.4.2 Limited Rainfall Resulting in Low Water Volumes



Source: Volta River Authority

Figure 3 Water levels in the Volta Lake reservoir

Ghana’s first experience of a power crisis in 1983 is mainly attributed to severe draught with devastating effects across the entire West African sub-region (Brew-Hammond and Kemausuor,

2007). Ghana has been heavily reliant on its main hydropower dam over the years. This reliance has always resulted in supply difficulties whenever rainfall patterns change and the inflow of water into the catchment area of the dam is disrupted. The turbines (some) of the hydropower plants are shut down during such periods, resulting in lower generation and supply. Figure 3 below graphs water levels in the Volta lake reservoir (the catchment area for water inflow for the Akosombo hydropower dam) over the years (1995 – 2006).

The minimum reservoir elevation level for the operation of the Akosombo dam is depicted by the red horizontal line (240 feet). The troughs circled in red indicate the crisis years. Three of the aforementioned crisis years are clearly marked out. It is however observed that the trough between 2003 and 2004 is not marked out as a crisis point; a case that goes to reinforce the argument of Brew-Hammond and Kemausuor, (2007) regarding the causes of power crisis in Ghana. This reinforcement stems from the fact that generation for the period was augmented by the purchase of diesel generators for power supply.

2.4.3 Population growth, industrialization and urbanization

Ghana, over the years, has experienced rising income levels with positive growth rates since 1984. Real GDP reached an all-time high of 15% in 2011 with a corresponding per capita income growth of 12% in the same year (Mensah et al., 2016). Further, the economy has undergone major structural changes that has seen industry and service take over from agriculture as the greatest contributors to total output. Mensah et al (2016), notes that “The implication of the sustained economic growth over the years and the changing structure of the economy is that energy demand is likely go up as more firms expand their plant size, households on average are becoming richer and all sectors particularly the emerging petroleum subsector's energy requirements surge”. Additionally, Duku et al. (2011), also notes that “Ghana's energy demand in recent years has increased significantly due to population increase (average growth rate of 2% per annum) and rapid urban growth (average growth of 4% for the period 1980–2013). These observations reflect rather well in the electricity consumption patterns over the years.

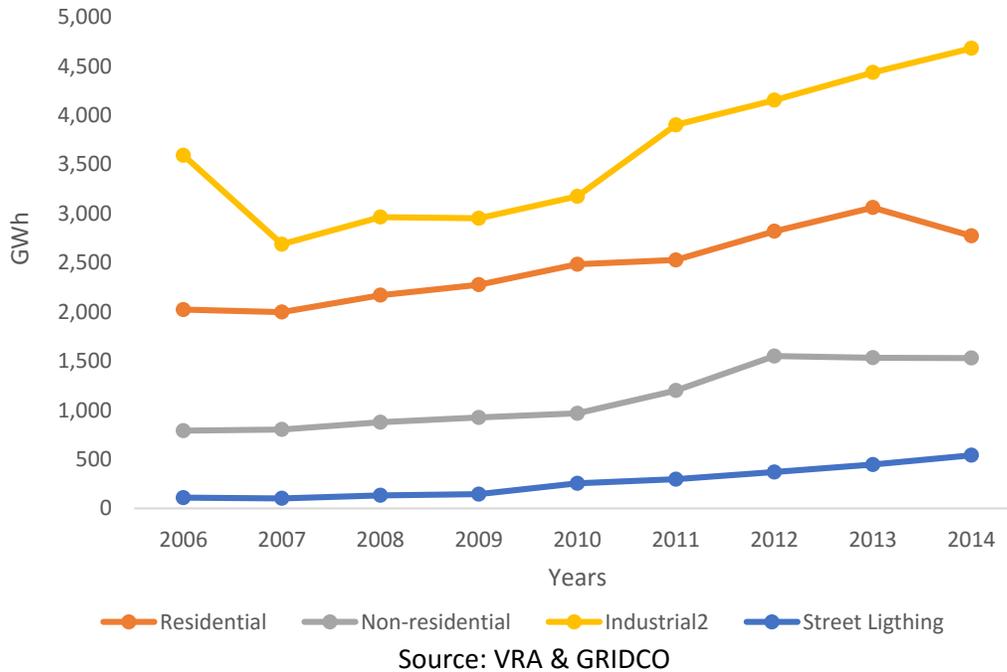


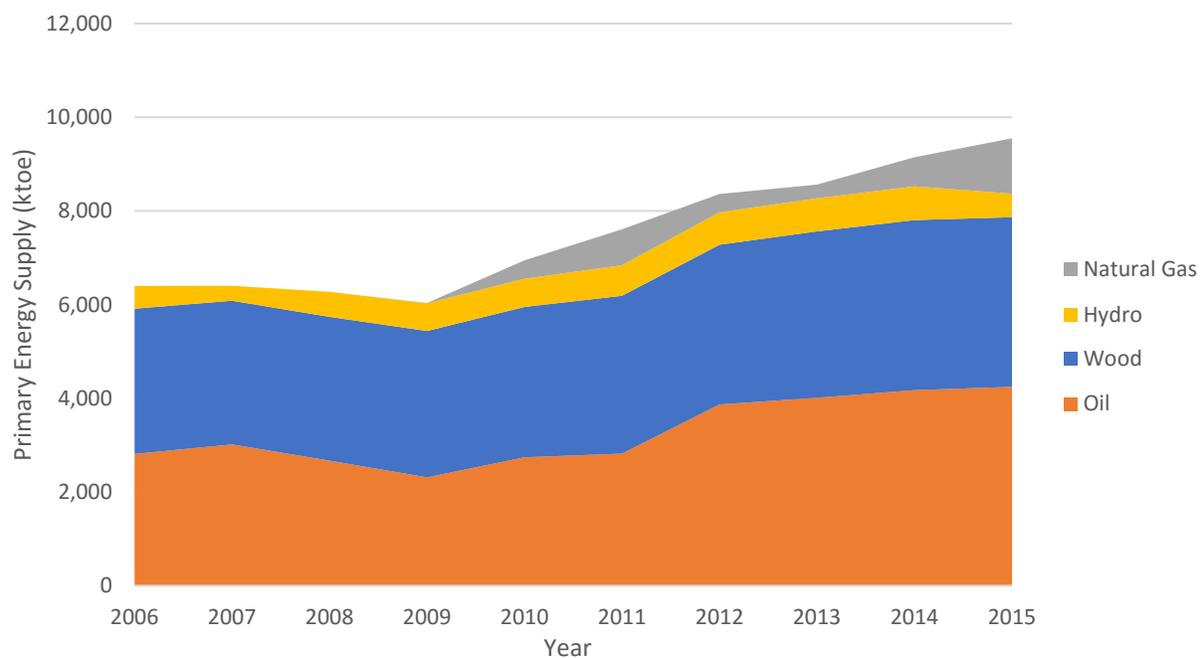
Figure 4 Electricity consumption according to consumer classification (2006 - 2014)

Figure 4 shows the electricity consumption trends amongst different classes of consumers from 2006 to 2014. All four classes of experienced an upward trend in consumption over the years (the only exception being residential consumption in 2014). As the population grows and becomes increasingly wealthier, energy demand grows. More so, industrial and street lighting electricity consumption trends clearly depict the spate of urbanization over the years. Despite the decline in 2007, industrial electricity consumption grew by about 74% from 2007 to 2014 while street lighting grew by approximately 400% over the same period. With such trends, the current energy access policy of government, aimed at increasing electricity coverage in a bid to increase energy access will only lead to further growth in demand.

2.5 Energy policy and resource potential of Ghana

2.5.1 Overview of Policies in the Ghanaian Energy Sector

Total energy consumption of Ghana was 7.2 million tons of oil equivalent (MTOE) in 2015. Total primary energy consumption as at 2015 was 0.26 tons of oil equivalent (TOE) per capita; one of the lowest in the world (Energy Commission of Ghana, 2016). Meanwhile, Ghana is endowed with a wealth of energy sources including hydro energy, biomass, hydrocarbons, solar irradiation, wind and tides. However, biomass and oil dominate the country's energy supply mix;



Source: National Energy Statistics - 2016 (Energy Commission of Ghana)

Figure 5 Trends in Primary Energy Supply in Ghana

accounting for about 90% of primary energy supplies.

As Figure 5 above depicts, hydro energy takes the third place after biomass and hydrocarbons as of 2015. Hydro energy has played a critical role in Ghana's electricity supply history over the years. Despite Ghana's endowment in energy resources, the large majority of these resources remain untapped. Several policies and operational guidelines have been adopted over the years to provide guidance and fiscal incentives for the development of the energy sector in Ghana.

Energy planning and policy development commenced in Ghana in 1990 under a National Energy Board. The board was established to undertake energy planning and policy development for the country with a focus on five main areas: Renewable Energy development, LPG promotion, Electricity Sector, the Petroleum Sector and Energy Efficiency and Conservation (Energy Commission - Ghana, 2006). Subsequent to this, several energy sector related policies and strategy documents have been formulated, including; the Strategic National Energy Policy (2006), National Energy Policy / Energy Sector Strategy and Development Plan, Ghana Shared Growth and Development Agenda, Renewable Energy Act, 2011 and the Country Action Plan for Sustainable Energy for All (SE4All).

2.5.1.1 Strategic National Energy Policy (SNEP)

SNEP is a comprehensive examination of Ghana's available energy resources with considerations for how and when to tap them economically to ensure a secure and adequate energy supply for sustainable economic growth to 2020 (Energy Commission - Ghana, 2006).

SNEP was set out with a vision to "...to develop an 'Energy Economy' that would ensure sustainable production, supply and distribution of high quality energy services to all sectors of the economy in an environmentally friendly manner for Ghana's future while making significant contribution to the country's export earnings" (Energy Commission - Ghana, 2006). Ten (10) broad objectives were defined under SNEP, including;

1. Stimulate economic development by ensuring that energy plays a catalytic role in Ghana's economic development.
2. Consolidate, improve and expand existing energy infrastructure.
3. Increase access to modern energy services for poverty reduction in off-grid areas.
4. Secure and increase future energy security by diversifying sources of energy supply.
5. Accelerate the development and utilization of renewable energy and energy efficiency technologies.
6. Enhance private sector participation in energy infrastructure development and service delivery.
7. Minimize environmental impacts of energy production, supply and utilization.
8. Strengthen institutional and human resource capacity and R & D in energy development.

9. Improve governance of the Energy Sector.
10. Sustain and promote commitment to energy integration as part of economic integration of West African states.

Under SNEP, amongst other projections, the EC projects that by 2020, for purposes of driving the Ghanaian economy to achieve a US\$1000 per capita by 2015 and consequently, maintain a middle-income status to 2020, the electricity component of national energy requirements will have to be about 16,300 GWh by 2015 and 23,000 GWh by 2020. A projection of 35 million tons is also made for biomass by 2015 and 50 million tons by 2020.

SNEP recognizes the fact that, in Ghana, "...except for woodfuels, almost all the components of the energy technologies are imported" and "provides the opportunities for the development of viable local industry for the production of components and systems locally, to meet future spare-parts requirements of future investments thereby making savings and ensuring sustainability" (Energy Commission - Ghana, 2006).

Additionally, SNEP recognizes the impact of energy systems on the environment. SNEP recognizes that energy technologies have risks, wastes and interacts with the environment; with impacts being both direct and indirect.

SNEP's full potential has not been achieved owing to several challenges. As the International Renewable Energy Agency (2015) puts it, "The plan identified renewables (including wind, solar and biomass) as key energy sources for long-term development and sustainable electricity supply. Unfortunately the huge potential of SNEP to create a market for renewable energy was not fully realized. This is because it was not formally adopted by the government. One of the challenges facing renewables development today is finding a way to redress this situation and make SNEP a binding policy document."

2.5.1.2 National Energy Policy/Energy Sector Strategy and Development Plan

In 2010, Ghana's Ministry of Energy published its Energy Sector Strategy and Development Plan. The plan document outlined the vision for the energy sector of Ghana's economy as being "...to ensure availability of and universal access to energy services and for export by 2020" (Ministry of Energy, 2010a). In order to achieve this vision, four challenges were identified to be surmounted;

1. Developing infrastructure for the production and supply of adequate energy services to meet national requirement and for export;
2. Developing the requisite infrastructure to ensure universal access as well as the efficient and reliable supply of energy services;
3. Ensuring that energy is produced and supplied in a form that has no adverse health, safety and environmental impact; and
4. Ensuring that energy is produced, transported and used in an efficient manner

The policy covered a broad spectrum of challenges relating to energy sub-sectors including;

- a. Power Sub-sector
- b. Petroleum Sub-sector
- c. Renewable Energy Sub-sector
- d. Waste-to-Energy
- e. Energy Efficiency and Conservation
- f. Energy and Environment
- g. Energy and Gender; and
- h. Managing the future of the sector.

The policy reiterates the vision of building an 'Energy economy' and further defines desirable goals to be met under each of these sub-sectors. For instance, for the power sub-sector, the policy sets the goal of increasing installed power generation capacity *quickly* from about 2,000 MW (in 2010) to 5,000 MW by 2015, and increasing electricity access from of 66% (in 2010) to universal access by 2020. Additionally, it indicates the desire to improve production and promoting efficient use of biomass in the short-term and switching from biomass to alternative energy sources.

2.5.1.3 Renewable Energy Act, 2011

In line with the pursuance of Ghana’s energy vision, a Renewable Energy Law (Act 882) was adopted to provide fiscal incentives and regulatory framework to encourage private sector investment (International Renewable Energy Agency, 2015). This law encompass 87 provisions including; Feed-in Tariffs (FiT), Renewable Energy Purchase Obligations (RPO), Net Metering (distributed generation), Off-grid Electrification for Isolated Communities, Promotion of Clean Cook stoves, Research and Development, Renewable Energy Fund (RE Fund), and the establishment of a Renewable Energy Authority (REA)” (International Renewable Energy Agency, 2015).

The Renewable Energy Act reiterates the ‘Energy Economy’ vision of previous policies. It states the sector goal as creating “...a developed ‘energy economy’ with reliable high quality energy services”. The government therefore established four national energy goals in order to achieve this vision (Ministry of Power, 2015);

1. Universal access to electricity by 2020 (recently moved forward to 2016) from 70% in 2011 (though access in rural areas is only 40%) –a slight improvement from the 2010 figure of 66%;
2. Attaining 5,000 MW of generation capacity by 2020 (recently moved forward to 2016);
3. 10% contribution of renewable energy (excluding hydro 100 MW or larger) in the electricity generation mix by 2020; and
4. Access to liquid petroleum gas (LPG) by 2020 for 50% of the population.

2.5.1.4 Ghana Shared Growth and Development Agenda II

The Ghana Shared Growth and Development Agenda (GSGDA II), spanning 2014 to 2017, is Ghana’s current medium term national policy growth and development framework. This is built on lessons learnt from previous GSGDA (from 2010 to 2013) (International Renewable Energy Agency, 2015). Ghana’s current medium-term national development policy framework, the Ghana Shared Growth and Development Agenda (GSGDA), seeks to achieve and maintain macroeconomic stability, underpinned by a monetary policy framework that targets low inflation, in order to achieve increased levels of shared growth with job creation, lesser socio-economic inequalities and reduced poverty, and the achievement of MDGS targets (Government of Ghana,

2012). The GSGDA II identifies power as the major binding constraint to the accelerated economic growth and development of the economy. GSGDA II notes that that: “In the medium-term, Government policy will focus on increasing the proportion of renewable and other sources of energy in the supply mix, particularly solar, wind, mini-hydro and waste-to-energy. The strategies to be implemented will include:

- a. Accelerating the implementation of the 87 provisions of the Renewable Energy Act 2011, Act 832;
- b. Providing access to waste-to-energy technologies; and
- c. Facilitating access to the grid for stand-alone renewable energy power plants.”

2.5.1.5 Country Action Plan for Sustainable Energy for All (SE4All)

Under the Country Action Plan for SE4ALL, the Government of Ghana recognizes the role effective and sustained access to energy plays in improving people's living conditions, while contributing to economic and human development (Government of Ghana, 2012). The country action plan for SE4ALL outlines the nation's adoption of "...a Sustainable Energy for All Acceleration Framework (SEAAF) to analyze constraints and identify and initiate concrete commitments and actions towards the three objectives of "Sustainable Energy for All."

The objectives outlined under the SE4ALL include;

- a. ensuring universal access to modern energy services,
- b. doubling the rate of improvements in energy efficiency, and
- c. doubling the share of renewable energy in the global energy mix,

These objectives are in line with the Ghana's National Energy Policy, GSGDA II and Renewable Energy Act, creating the necessary stimulus for a coerced front on implementation and achievement of the desired objectives. The thrust of projects proposed under the Ghana SE4ALL Country Plan is two pronged - the development and promotion of small-scale productive opportunities for value-addition in communities, and the use of mechanical power to enhance production and efficiency (Government of Ghana, 2012).

2.5.2 Energy resource potential of Ghana

Ghana is energy-resource endowed with energy sources including biomass, wind, hydro, tides and petroleum. Despite the endowment, the useful energy derivable from these sources tend to be limited by various factors including natural phenomena and technology used in their conversion from source to power. Several studies have sought to assess and quantify Ghana's various energy sources. A notable study of the sort is the Solar and Wind Energy Resource Assessment (SWERA) funded by Global Environmental Facility (GEF) and United Nations Environment Program (UNEP) and undertaken by US institution NREL (National Renewable Energy Lab) worked with the Ghana Energy Commission and Meteorological Service. We briefly discuss Ghana's energy resource potential below;

2.5.2.1 Solar Energy Resource

The solar irradiation level in Ghana ranges from 4.5 to 6.0 kWh/m²/day with the highest irradiation levels occurring in the northern half of the country (Schillings et al., 2004; Ministry of Power, 2015).

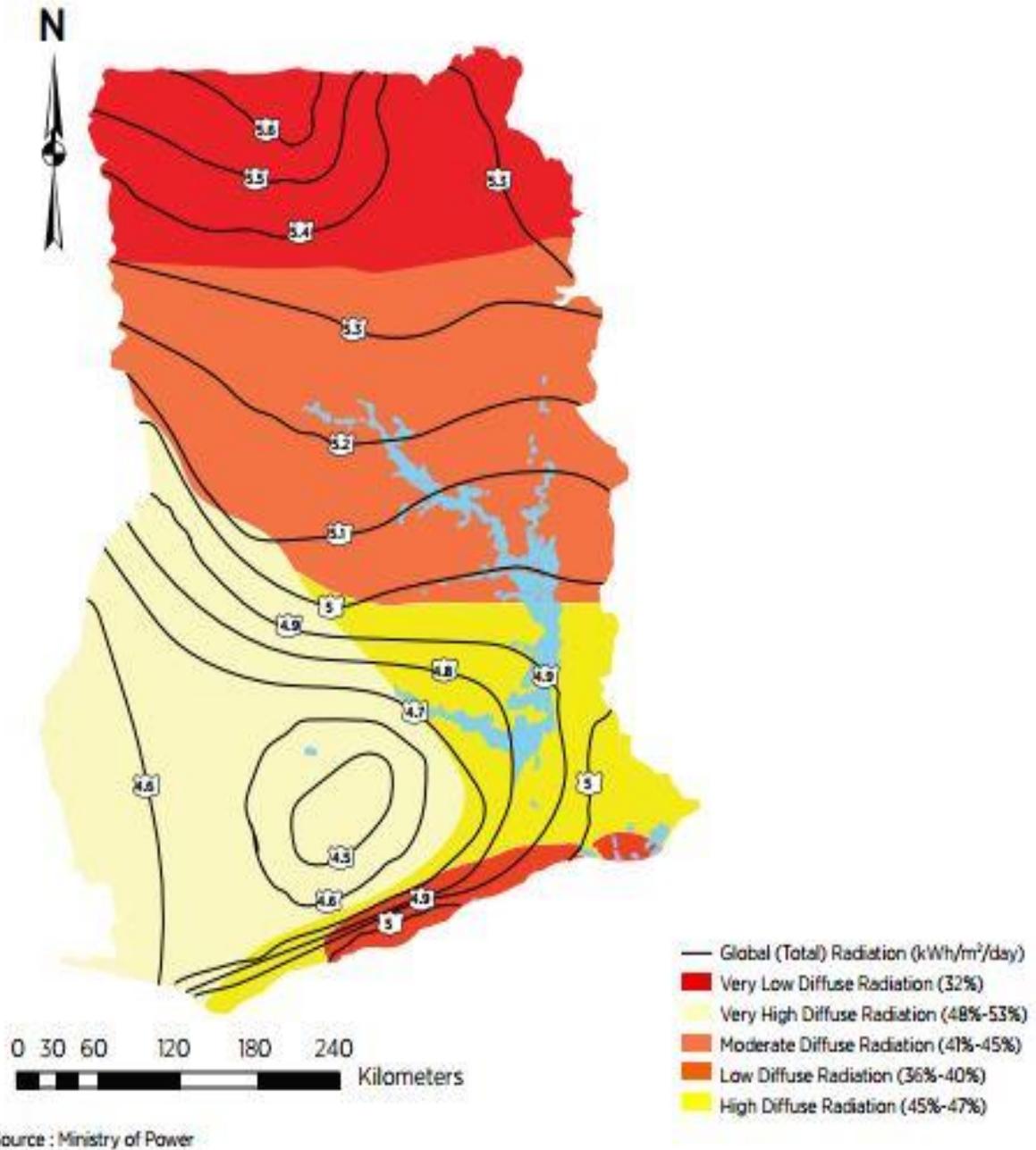
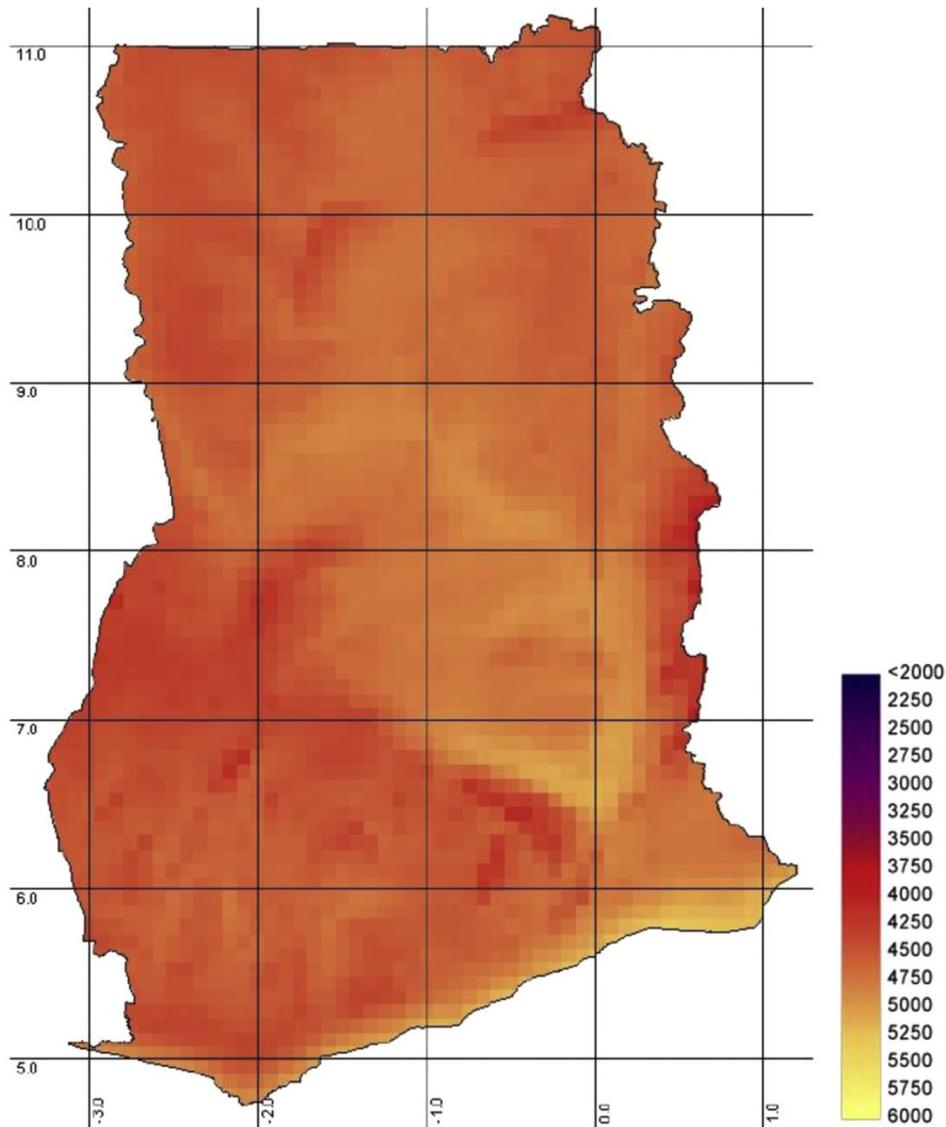


Figure 6 Global Solar Irradiation in Ghana



Source: Extract from Gyamfi et al. (2015)

Figure 7 Ghana's annual average total daily sum of GHI in Wh/m²/day (3-years average)

Figure 7 shows the global solar irradiation in Ghana in terms of diffuse radiation whiles Figure 7 shows the annual average total daily sum of GHI in Wh/m²/day of Ghana. Gyamfi et al. (2015), points out that, most parts of the country receive 5 to 8 hours of sunshine at 1 MWh/m²/day. Sunshine availability for such long hours avails a huge opportunity for achieving a number of goals in the energy sector.

At an average of 6.5 hours of sunshine per day, Ghana enjoys approximately 2,372 hours of sunshine in a year; resulting in over 2,800 trillion KWh of energy across Ghana's land mass.

Table 3 Solar energy related statistics in Ghana

Descriptions	Quantities
Land mass (km^2)	238,535
Land mass (m^2)	238,535,000,000
Average sun annual Sun hours	2372
Average solar energy potential per m^2	5 kWh
Energy potential across Ghana's land mass (kWh)	2,829,025,100,000,000

Table 3 shows the statistics deriving the solar energy potential across Ghana’s land mass. Even at a conversion efficiency rate of 15%, and notwithstanding all the challenges/limitations of harvesting and storing solar energy, solar irradiation provides substantial derivable useful energy across the country.

Solar energy has the potential to afford Ghana a means of achieving her energy sector objectives of electricity access, renewable energy integration into the energy mix and ‘limited’ reliable supply of power (limitation considers the challenges of intermittency, storage and day-night cycle).

This potential notwithstanding, consideration needs to be given to the fact that, the nation cannot engage its entire land surface area for solar energy production. Human activity requirements in the likes of infrastructure, agriculture, industry and the dictates of urbanization and population growth regarding the ever increasing need for space, will require some surface area as well.

2.5.2.2 Wind Energy Resource

Wind energy related measurements in Ghana dates as far back as 1921 by the Meteorological Services Department for meteorological and agricultural requirements. Wind speeds were measured at selected sites at 2 m above ground level (a.g.l). The recorded results indicated wind speeds of approximately 2.4 m/s at this height. In 1999, the Energy Commission of Ghana started wind energy resource measurement along the coast of Ghana with the view to develop adequate, accurate and reliable wind energy data and evaluation tools as an integral part of Ghana’s energy planning and policy framework (Energy Commission - Ghana, 2005). Data gathered by the Energy Commission at 12 m (a.g.l) indicated wind speeds ranging between 4.8 m/s to 5.5 m/s. According to the U.S National Renewable Energy Laboratory (2002), “The maximum energy that could theoretically be tapped from the country’s available wind resource for electricity using

today's technology is about 500 – 600 GWh per year". This observation is as a result of an assessment that covered the whole of Ghana with the primary focus being the potential for large-scale grid-connected wind turbines (Gyamfi et al., 2015).

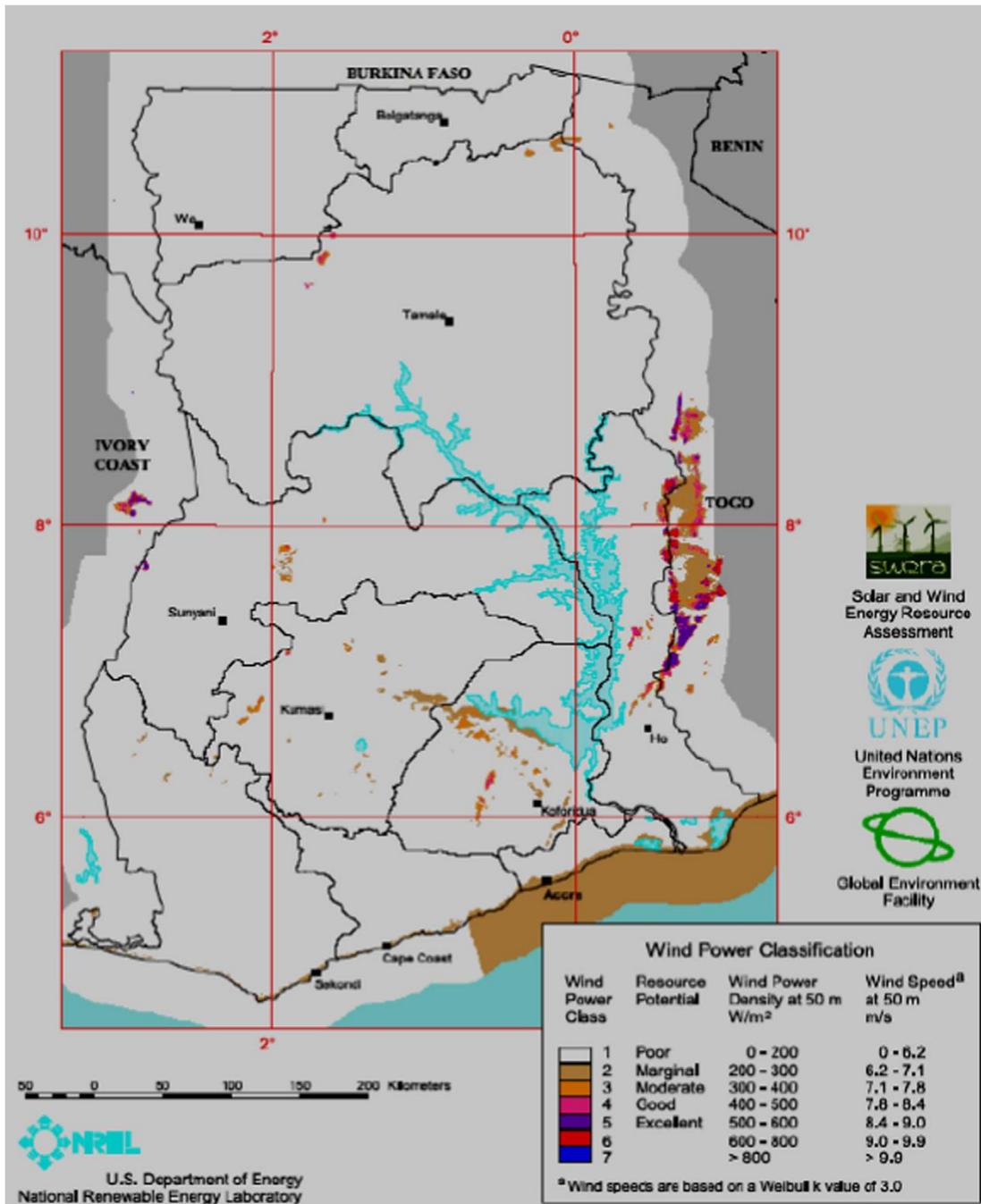


Figure 8 Wind energy resource map of Ghana (wind speed at 50 m height)

Figure 8 shows NREL’s wind energy resource map of Ghana with measurements taken at a height of 50 m. Gyamfi et al. (2015), further notes that “According to SWERA maps, the strongest wind regime (wind speed 7.8–9.9 m/s) occurs along the eastern border with Togo, and that can yield a wind-power density of 600–800 W/m² in the area of about 300–400km²”. The SWERA assessment projects identified total wind power potential in Ghana at a 50 m height to

Good-to-Excellent Wind Resource at 50 m

Wind Resource Utility Scale	Wind Class	Wind Power at 50 m W/m ²	Wind Speed at 50 m m/s*	Total Area km ²	Percent Windy Land	Total Capacity Installed MW
Good	4	400 – 500	7.0 – 7.5	268	0.1	1,340
Excellent	5	500 – 600	7.5 – 8.0	82	<0.1	410
Excellent	6	600 – 800	8.0 – 8.8	63	<0.1	315
Total				413	0.2	2,065

Moderate-to-Excellent Wind Resource at 50 m

Wind Resource Utility Scale	Wind Class	Wind Power at 50 m W/m ²	Wind Speed at 50 m m/s*	Total Area km ²	Percent Windy Land	Total Capacity Installed MW
Moderate	3	300 – 400	6.4 – 7.0	715	0.3	3,575
Good	4	400 – 500	7.0 – 7.5	268	0.1	1,340
Excellent	5	500 – 600	7.5 – 8.0	82	<0.1	410
Excellent	6	600 – 800	8.0 – 8.8	63	<0.1	315
Total				1,128	0.5	5,640

* Wind speeds are based on a Weibull k value of 2.0

Assumptions

Installed capacity per km² = 5 MW

Total land area of Ghana = 230,940 km²

Source: SWERA - Ghana Wind Energy Resource Mapping Activity report

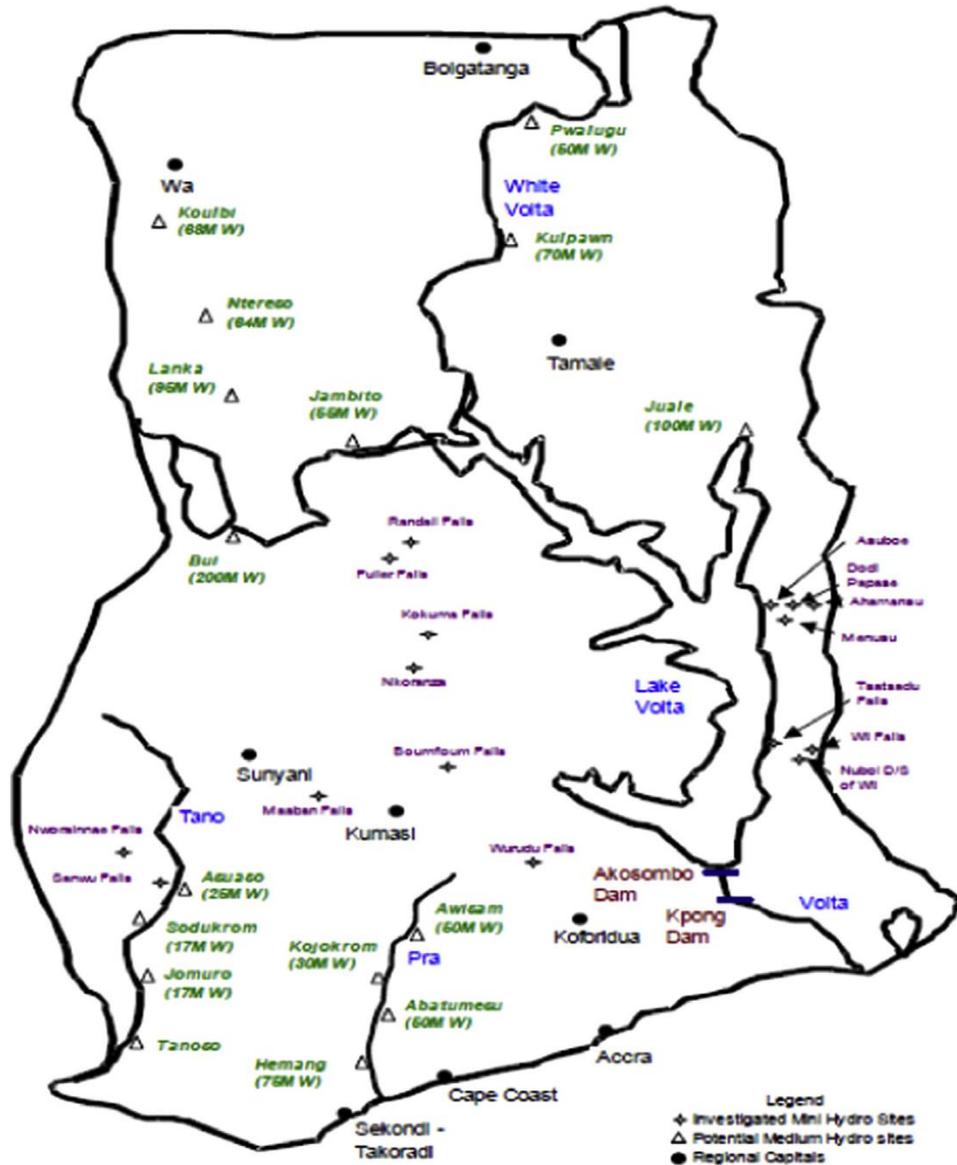
Figure 9 Ghana - Wind Electric Potential

be about 2000 MW. Figure 9 below shows the estimates of windy area and potential wind capacity in Ghana as identified by SWERA.

As depicted in Figure 9 above, the addition of moderate wind resource increases the wind power potential in Ghana from just over 2000 MW to over 5,600 MW at a measuring distance of 50 m. Recent wind power assessments being carried out have measurements being taken at 40 m, 50 m and 60 m across 5 wind resource sites with higher wind speeds being recorded (Gyamfi et al., 2015).

2.5.2.3 Hydro Energy Resource

Ghana has an additional estimated hydropower potential 800 MW extractable from small and medium-scale hydro sources. There are about 17 medium and 22 mini/small hydropower sites with exploitable capacities ranging from 15 kW to 100 MW (Ministry of Power, 2015).



Source: Extract from Gvamfi et al. (2015)

Figure 10 Distribution of small and medium hydro resources in Ghana

Figure 10 shows the distribution of small and medium hydro resource sites across Ghana. The government has commenced a number of projects in line with developing the some of these sites

in a bid to harness some more of the hydro power potential of the country. A number of these projects are being undertaken with development partners across the country.

2.5.2.4 Biomass Energy Resource

Biomass has been a major source of energy throughout the world. Biomass accounts for nearly 50% of the primary energy source of almost half the population of the world (Karekezi and Kithyoma, 2006). Biomass resources, in Ghana, cover about 20.8 million hectares of the 23.8 million hectare land mass of the nation and supplies about 64% of the total energy used in the country. Biomass is Ghana's dominant energy resource in terms of endowment and consumption. Biomass is used in the domestic sector for cooking, and for many other applications, such as water heating. Biomass is also used in many educational establishments throughout the country (Ministry of Energy, 2010b; Gyamfi et al., 2015).

Ghana has vast arable land mass suitable for the cultivation of varied crops and plants that can be converted into a wide range of biofuels. Large amounts of agricultural by-products/residues that can be used for energy production are generated from agro activities in the country (Gyamfi et al., 2015). According to Government of Ghana (2012), there is an estimated 553,000 t of maize cob and stalk produced with a potential energy of 17.65–18.77 MJ/kg and 19 t of paddy rice husks with a potential energy of 16.14 MJ/kg. Additionally, 193,000 t of oil palm shells, 136,000 t of sorghum stalks, 150,000 t of millet stalks and 56,000 t of groundnut shells were produced that.

Duku et al. (2011), also notes that “In Ghana, a large scope exists for the exploitation of different types of biomass, such as energy crops, agricultural and forestry residues, wood processing wastes, and municipal solid waste for conversion to biofuels using different routes”. In Ghana, potential exists, for the exploitation of these biomass types, especially for food wastes to be digested using anaerobic process to produce biogas, or fermented to produce ethanol (Duku et al., 2011).

The transport sector has been the key area for large-scale efforts in biofuel use worldwide (Duku et al., 2011). It is therefore instructive to note that, “Through its Bioenergy Policy, Ghana seeks to improve oil supply security, save foreign exchange, create jobs and reduce emissions from the transport sector by integrating 20% biofuels into the transport fuel mix by 2030” (Iddrisu and Bhattacharyya, 2015).

2.5.2.5 Petroleum

In 2007, Ghana discovered recoverable petroleum resources in commercial quantities along her western coast. Following these discoveries, Ghana's continental margin has seen various petroleum related exploratory activities with a number of these activities resulting in finds.

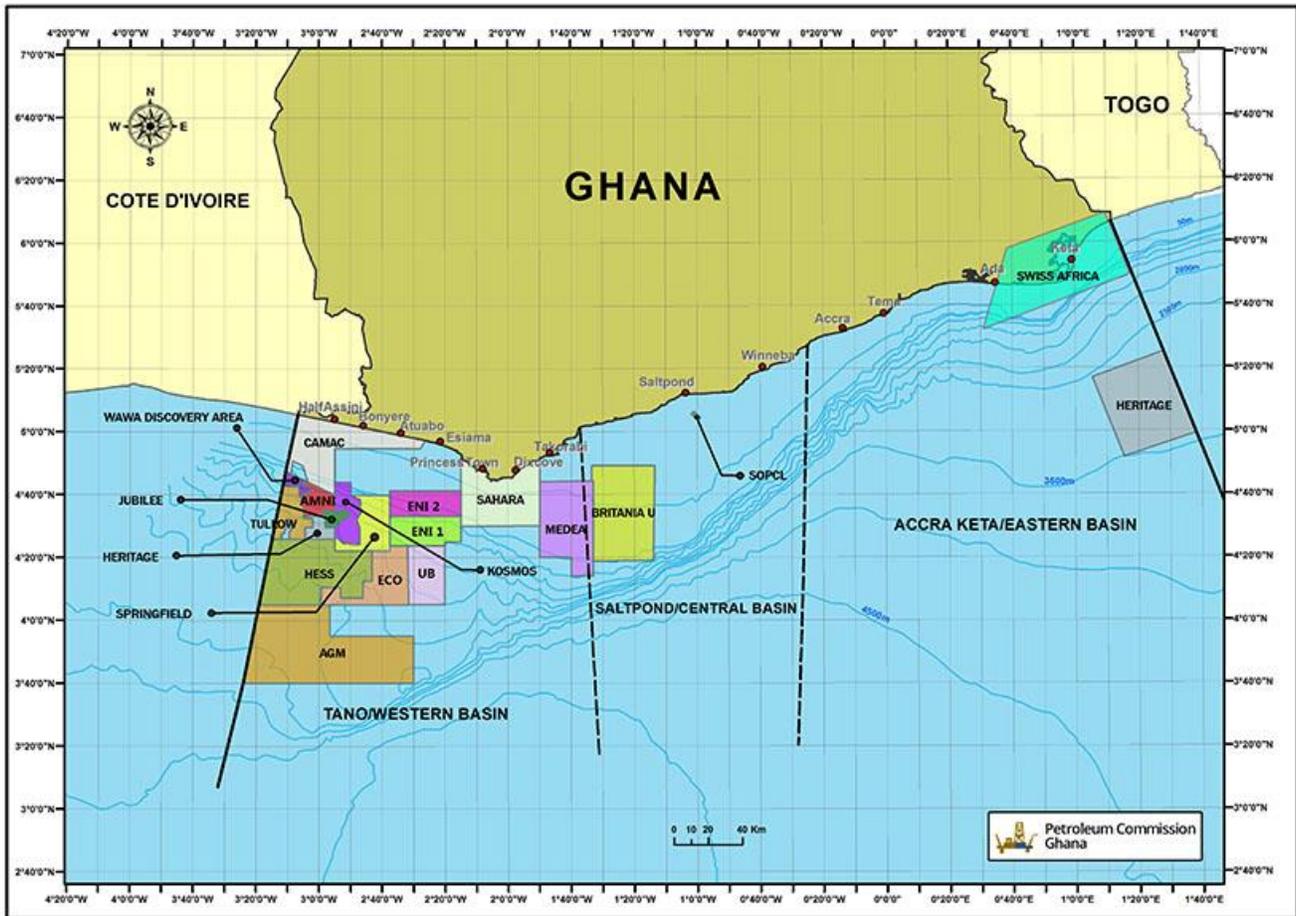


Figure 11 Offshore activity map of Ghana's petroleum exploration industry

Figure 11 shows Ghana's offshore activity map with respective energy companies and their demarcated blocks. Most of the finds made are currently in an appraisal state with some in an appraised state. Two blocks are currently in a development state as per Figure 12 below. Figure 12 lists the current exploration blocks and their current status. Two blocks, Deep Water Tano and Offshore Cape Three Points, are in a development state and currently producing.

Oil from Ghana's wells are noted to be light and sweet with an API of 37.6 degrees and a sulfur content of 0.25% (weight). Ghana's recoverable reserves have been estimated at 3 billion barrels of oil and 1.4 billion barrels of oil equivalent from the Jubilee and Tweneboa-1 fields

respectively (Kastning, 2016). Ghana's proven gas reserves are concentrated in three large offshore gas fields: the Jubilee field with associated gas reserves estimated at 490 Billion cubic

Contact Area	Operator	Discoveries	Discovery Date	Hydrocarbon Type	Status
Expanded Shallow Water Tano	Erin (CAMAC) Energy	North Tano South Tano West Tano	Philips-1980 Philips-1978 Dana-2000	Oil	Appraised
Shallow Tano	Interoil	Ebony	November 2008	Gas/Condensate	Marginal/Relinquished
Deepwater Tano	Tullow Oil	Tweneboa-1	March 2009	Gas condensate	Development
		Tweneboa-2	January 2010	Oil	Development
		Owo/Enyenra-1	September 2010	Oil	Development
		Ntomme	January 2012	Oil and Gas	Development
		Wawa	2012	Oil and Gas	Appraisal
West Cape Three Points	Kosmos Energy	Odum-1	February 2008	Heavy Oil	Relinquished
		Teak-1	February 2011	Oil and Gas	Appraised
		Teak-2	March 2011	Gas	Appraised
		Banda-1	June 2011	Oil	Relinquished
		Mahogany Deep	January 2009	Light Oil	Appraised
		Akasa-1	August 2011	Light oil and Gas	Appraised
Offshore Cape Three Points	ENI	Sankofa-1	September 2009	Gas	Development
		Gye Nyame-1	July 2011	Gas	Development
		Sankofa East	December 2012	Oil and Gas	Development
Deepwater Tano Cape Three Points	Hess	Paradise-1	July 2011	Oil and Condensate	Appraisal
		Hickory North-1	May 2012	Oil and Condensate	Appraisal
		Almond-1	September 2012	Oil and Condensate	Appraised
		Beech-1	August 2012	Oil	Appraised
		Cob-1	January 2013	Oil	Appraisal
		Pecan	December 2012	Oil	Appraised
		PN-1	February 2013	Oil	Appraised
Deepwater Cape Three Points	Lukoil	Dzata-1	February 2010	Oil and Gas	Relinquished
		Lynx-1X	July 2014	Oil and Gas	Relinquished

Figure 12 List of discoveries and their state

feet (Bcf), the TEN fields with associated gas reserve of 363 Bcf and the Sankofa field with non-associated gas reserves of 1,107 Bcf. In addition, the Mahogany and Teak discoveries with total reserves of 120 Bcf will be developed as part of the Greater Jubilee Full Field (Ministry of Petroleum, 2016).

3 Theoretical Perspectives

3.1 Energy Economics

Energy economics, a sub-discipline of economics, is a broad scientific subject area which includes topics related to supply and use of energy in societies (Sickles, 2008). Energy economics thus concerns itself with the study of human utilization of energy and the consequences of that utilization. Energy economics tends to be an applied sub-discipline of economics. The field inculcates aspects of several disciplines including finance, resource economics, environmental economics, industrial organization and engineering.

Energy, in economic terminology, includes all energy commodities and energy resources that embody significant amounts of physical energy and thus offer the ability to perform work. Energy economics studies forces that lead economic agents (firms, individuals, governments) to supply energy resources, to convert those resources into other useful energy forms, to transport them to the users, to use them, and to dispose of the residuals (Sweeney, 2002).

Access to energy has become a necessity of modern societies. The field lends itself to balancing the energy demand and supply equation; meeting human energy needs by making use of available energy resources. *Ceteris paribus*, due to uneven distribution of energy resources, a country's energy supply may be exposed to disruptions and hence the need for policy planning is crucial in addressing issues of energy development including energy production, distribution and consumption.

Disruptions in a country's energy supply may have economic, political and stability implications for the said country. Owing to this, energy economics, sometimes, tends to focus on the provision of sufficient energy to meet demand. Yergin, 2006, defines energy security as "...the availability of sufficient supplies at affordable prices". The supply and availability of energy to meet demand is largely reliant of on the ability for its generation in the form needed.

Providing the needed energy requires careful planning and economic measures of power generation systems to ensure optimal returns from the system that may be chosen for power generation. A number of economic measures may be employed in assessing investment decisions on power generation systems. These include;

- Real Option
- Net present value (NPV)
- Levelized Cost of Energy (LCOE)

3.1.1 Real Option Analysis

The irreversibility of investments in energy projects associated to the uncertainty in the future value of these projects give rise to an opportunity cost related to the timing of the investment. When facing an investment decision, an investor can either choose to invest now or to wait and keep the possibility of not investing open (Dixit and Pindyck, 1994). Waiting can, in some cases, help the investor reduce the uncertainty attached to costs and revenues. Therefore, waiting has a value (known as a real option value) which will drop to zero as soon as the investment is made, because the investor will not be able to benefit from any new information that would potentially have led the investor to adapt her investment decision otherwise. Whenever possible, in the sense that it is cost effective, the value of this option should be integrated in the traditional net present value (NPV value) rule that the investor will apply to decide whether an investment is sound or not.

There are several types of real options. The common type is known as a ‘defer option’, i.e. the value of waiting. Another relevant real option in the energy field is the ‘growth option’, which is related to the possibility to expand an energy project in the future (Fernandes et al., 2011). The value of this option is particularly high for energy projects that can be built in modules, since such projects can more flexibly adapt to changing market conditions. For example, if a power plant is built to match the growing energy demand, it is possible that future growth prospects are highly uncertain. In this case, the flexibility value offered by a plant to which subsequent units can be added at will, needs to be taken into account if compared to the construction of a larger, inflexible plant. The former type allows the investor to retain some of the real option value. And if bigger plants usually lead to better economies of scale compared to more flexible plant, then the investor will favor flexibility under the real option approach until the value of the economies of scales exceeds the value attached to this flexibility (Narbel et al., 2014). Compared to the NPV approach, the NPV approach typically ignores flexibility.

3.1.2 Net Present Value (NPV)

Investments in energy projects are characterized by their irreversibility as investment costs will generally be sunk. Investments in wind turbines and solar panels are example of irreversible investments as these will be used until they fail to generate energy, in which case their residual value will be close to zero. Several techniques are available to evaluate the expected economic outcome of an irreversible investment. The net present value approach (NPV) is the most common of them. It is an approach which can help determine whether a project's financial outcome is expected to be positive or negative. The NPV integrates the initial investment in a project as well as the expected revenues and costs over time, and transforms them in a series of cash flows adjusted by the time value of money and risk. The basic NPV formula is given as;

$$V_{NPV} = -I + \sum_{t=0}^T \frac{C_t}{(1+r)^t}$$

Where;

$-I =$ Initial Investment

$C_t =$ Net cash inflow during period t

$t =$ number of time periods

$r =$ Rate of discount

Costs and revenues must be estimated in the most accurate manner in order to lead to useful insights on the financial attractiveness of an investment. A key element of the NPV equation is the discount rate, which is needed to transform future cash flows in order to obtain their present value (Narbel et al., 2014). Failing to appropriately select the right discount rate has the potential to change the merit order between certain projects.

The discount rate is also very important because it puts a value on time preference of money (Branker et al., 2011) and thus allows for the comparison of projects with different economic lives and which costs occur at different times.

3.1.3 Levelized cost of Energy (LCOE)

The levelized cost of energy (LCOE) allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both exist. Thus, LCOE on allows the comparison of different energy technologies with different physical principles, fuels and economic plant life. According to Short et al., 1995, “LCOE is recommended for use when ranking alternatives given a limited budget simply because the measure will provide a proper ordering of the alternatives, which may then be selected until the budget is expended”. LCOE estimates is a good way to track and compare the financial cost competitiveness of different power generation technologies, taking into account the full project life-cycle from development to financing to construction and then operation. The LCOE has been designed with the idea of allowing for comparisons between energy sources on a unit cost basis over the lifetime of different energy technologies and projects.

LCOE can be calculated using the formula (Roth and Ambs, 2004),

$$LCOE = \left[\frac{R \times cp}{H \times f} \right] + \left[l \times \left(\frac{co}{H \times f} \right) \right] + \left[l \times \left(\frac{cf}{H \times f} \right) \right]$$

Where;

R is capacity recovery factor

cp is installed capacity

cf is cost of fuel

H is hours of operation in a year

f is capacity factor

co is operation and maintenance costs

l is the levelization factor

T is plant life time

r is discount rate

The LCOE may be split into three distinct elements namely, namely **capital costs, operation and maintenance costs and fuel costs.**

Capital Costs: Capital cost can vary among countries and regions even for the same type of energy projects; these include equipment costs such as turbines for wind farms, modules for solar panels, construction cost as well as land rents. This initial investment can be relatively small, for example a micro wind turbine, to very large such as nuclear plants or hydropower dams. In short capital cost or capex stands for the cost of the plant measured in monetary units by units of installed capacity, which will be labeled as *cp* (e.g.: USD/kW or Euro/MW). Capital costs may be calculated as;

$$\mathbf{Capital\ Cost} = \left[\frac{\mathbf{R} \times \mathbf{cp}}{\mathbf{H} \times \mathbf{f}} \right]$$

The capacity factor f is the power produced over a period of time divided by the power that may have been produced if the plant was running 100% of the time over the time period considered which is one year designated as H . As different energy plants have different life spans, the capital recovery factor R , denotes the share of the plant cost that the income must cover over each year of operation such as to balance out the whole project at the end of the plant life which takes into account the discount rate r and the economic plant life T . The recovery factor may also be calculated as;

$$\mathbf{Recovery\ Factor\ } R = \left[\frac{r \times (1+r)^T}{(1+r)^T - 1} \right]$$

Operations and Maintenance Costs: O&M costs consist of a fixed costs which does not change with levels of production and include annual administrative, rent/lease contract costs, insurance, wages. Variable O&M costs vary with levels of production and include annual fuel, carbon, and ad hoc maintenance fees. For practicality purposes, both variable and fixed O&M costs are grouped together under the label co as such data availability is insufficient.

The levelization factor l , under O&M, considers an increase of the O&M costs as the plant ages by taking into account the discount rate r and an escalation rate e which measures the rate at which O&M costs are expected to increase annually. O&M costs are calculated as

$$\mathbf{O\&M\ Cost} = \left[l \times \left(\frac{co}{H \times f} \right) \right],$$

and the levelization factor is calculated as

$$\mathbf{Levelization\ factor\ } l = \left[\frac{r \times (1+r)^T}{(1+r)^T - 1} \right] \times \left[\frac{(1+e)}{(r-e)} \right] \times \left[1 - \left(\frac{1+e}{1+r} \right)^T \right]$$

Fuel Costs: The cost of fuel cf , is expressed in a unit cost basis by factoring in the levelization factor, capacity factor and the number of hours in a year. This is also calculated as

$$\mathbf{Fuel\ Cost} = \left[l \times \left(\frac{cf}{H \times f} \right) \right]$$

3.2 Linear Optimization

Linear optimization (also called linear programming) is a sub-field of mathematical optimization that concerns itself with obtaining an optimal choice from available alternatives. Under linear programming, there is usually a function, called the objective function, which depends linearly on a number of independent variables and a set of constraints expressed in the form of equations and inequalities. The goal is to optimize the said function by finding either its minimum value or maximum value¹.

A standard linear optimization maximization problem may be defined as;

Find an n-vector, $\mathbf{x} = (x_1 + \cdots + x_n)^T$, to maximize

$$c^T \mathbf{x} = c_1 x_1 + \cdots + c_n x_n$$

subject to the constraints

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \leq b_2$$

⋮

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \leq b_m$$

And

$$x_1 \geq 0, x_2 \geq 0, \dots, x_n \geq 0 \quad (\text{or } \mathbf{x} \geq \mathbf{0})$$

A standard linear optimization minimization problem may also be defined as;

Find an m-vector, $\mathbf{y} = (y_1 + \cdots + y_m)^T$, to maximize

$$y^T \mathbf{b} = y_1 b_1 + \cdots + y_m b_m$$

subject to the constraints

¹ <http://www.math.uconn.edu/~stein/math1070/Slides/math1070-140notes.pdf>

$$y_1 a_{11} + y_1 a_{12} + \dots + y_m a_{m1} \geq c_1$$

$$y_1 a_{12} + y_2 a_{22} + \dots + y_m a_{m2} \geq c_2$$

⋮

$$y_1 a_{1n} + y_2 a_{2n} + \dots + y_m a_{mn} \geq c_n$$

And

$$y_1 \geq 0, y_2 \geq 0, \dots, y_n \geq 0 \quad (\text{or } y \geq 0)$$

A major factor in the equations above that is worthy of note is the inequality signs for the constraints of a maximization problem (\leq) and that of a minimization problem (\geq).

3.2.1 Assumptions under linear optimization

Proportionality:

The assumption of proportionality asserts that, there is a proportional relationship between the objective function and constraint inequalities such that changes in the constraint inequalities will result in a corresponding proportional change in the objective function. This implies that changes in each decision variable of a linear optimization model results in a proportionate change in its contribution to the value of the objective function.

Additivity:

The additivity assumption asserts that, the total value of the objective function is determined by the summation of the contributing values of each individual variable of the model. This implies that there is no interaction between any pair of variables and their contribution to the objective function.

Divisibility:

The assumption of divisibility asserts that the values of the decision variables can be fractional. This implies that a combination of outputs can be used; fractional values along with integer values.

The assumptions of proportionality, additivity and divisibility ensures linearity of linear optimization models.

Certainty:

The assumption of certainty asserts that, the parameters to the model (parameters of coefficients of both objective function and the constraints) are known with precision and certainty. In real life situations, where this assumption may not necessarily be accurate, reasonable approximations may be used.

3.2.2 Linear Optimization Problem Formulation

This involves the translation of problem statement into linear equations. The information required for the formulation of the objective function is obtained from the problem statement².

The problem formulation may be achieved by following the steps below;

- a. Identification of the objective of the problem
- b. Identification of the decision variables and their respective constraints
- c. Writing-out the objective function and constraints in terms of the decision variables. The coefficient of each term should be accurately derived from the problem statement.
- d. Addition of implicit constraints (for example non-negatives)
- e. Arranging the system of equations in a consistent form

² <http://www.netmba.com/operations/lp/>

3.2.3 Solution Methods

The simplex method is a method for solving problems in linear programming. This method, invented by George Dantzig in 1947, tests adjacent vertices of the feasible set (which is a polytope) in sequence so that at each new vertex the objective function improves or is unchanged (Weisstein, 2006). The simplex method to solving linear programming problems is an algebraic iteration method. The method is very useful with dealing with higher dimensional problems owing to ones inability to perceive the feasible region of the objective function geometrically.

Dantzig and Thapa, 2006, note two phases (Phase I and Phase II) in the application of the simplex method at solving linear programming problems. They state that “In Phase I a starting basic solution is sought to initiate Phase II or to determine that no feasible solution exists. If found, then in Phase II, an optimal basic feasible solution or class of feasible solutions with $z \rightarrow -\infty$ is sought”.

The Phase I procedures determine whether or not there are redundancies or inconsistencies with the problem definition and bears several important features (Dantzig and Thapa, 2006):

1. No assumptions are made regarding the original system; it may be redundant, inconsistent or insolvable in nonnegative numbers.
2. No eliminations are required to obtain an initial solution in canonical form for Phase I
3. The end product of Phase I is a basic feasible solution (if it exists) in canonical form ready to initiate Phase II.

The simplex algorithm for solving linear programming problems is defined in the following steps as;

Step I: Standardize the original systems of equations by modifying them so all constant terms are nonnegative

Step II: Using artificial variables, find an initial basic feasible solution

Step III: Check whether the initial basic feasible solution is optimal

Step IV: If the initial basic feasible solution is not optimal, find a new basic feasible solution with a better objective function value

Step V: Repeating Step III and Step IV until there is no better value of the objective function, indicating that the current value was optimal, or until it is clear that there is no optimal solution

Several solution methods and algorithms, outside of the simplex method, for solving linear programming problems. These include Affine Scaling, Criss-cross algorithm, Ellipsoid algorithm, and Path-following algorithms.

3.3 Literature Review and Related Works

According to Østergaard, 2009, generally, methodologies for optimizing energy mix can be subdivided into two schools of thought;

- a. Economic Optimization
- b. Techno-Operational Optimization

Vidal-Amaro et al., 2015, also notes that “When optimizing from a techno-operational standpoint, common criteria’s are reserve/backup capacity requirements, import and export dependence, Primary Energy Consumption (PEC) and fuel savings, Renewables shares, carbon dioxide emissions and Excess Electricity Production (EEP). Meanwhile, economic optimization utilizes societal costs or cost-benefit data, utility costs, rate impact, levelized cost of energy or levelized unit electricity costs, total resources spent by consumers, energy companies and government bodies, and marginal costs”. Additionally, Østergaard, 2009, observed that different optimization methodologies yielded different results. He concludes that “...no unequivocal answer can be found to the question of how to design an optimal energy system”. However, he further concludes that “the analysis shows that, when references are being made to specific renewable energy targets or to cities or areas with policy ambitions of changing to renewable energy or becoming carbon dioxide neutral, the optimization criteria need to be clearly defined

Form Østergaard, 2009, and Vidal-Amaro et al., 2015, it is clear that where techno-operational needs are concerned, economic optimization alone may not fulfil the requirements, rather it leans towards a business perspective on the feasibility of a project. A classic example would be the intermittency issues in renewable energy sources. Optimizing over a longer time frame based on

the lowest cost or LCOE may not capture the balancing issues. However, factors surrounding the problem statement that necessitates optimization may influence the choice of methodology.

Gyamfi et al., 2015, undertook a review of Ghana's assessed potential renewable energy resources, their current exploitation status and their potential contribution to electricity supply in Ghana. The outcome of their review indicated that Ghana has several renewable energy resources, including small/mini hydro, biomass, solar and wind that can be leveraged to meet growing annual energy demand. Focusing on the electricity market in eastern Japan, Saeko et al., 2010 developed an optimal power generation mix model in a bid to "investigate the operational impact on optimal power generation mix of large renewable energy deployment and develop sensitivity analysis with respect to nuclear capacity, capability of electricity interexchange among utility companies and carbon dioxide emissions regulation". The model, under various assumptions, sought to minimize total power generation cost, mainly consisting of facility cost and fuel cost. Using a Linear Programming method, the study stated that, in future power generation mix, solar and wind power were expected to become the center of renewable power supply sources. Further to their analysis, they confirmed that wind power generation when effectively adopted will lead to the reduction of carbon dioxide.

De Jonghe et al., 2011, also developed a model based on the screening curve methodology to include wind energy, using a static linear programming investment model to determine the optimal technology mix by determining the mix of technologies operating as base, intermediate and peak loads that are capable of meeting the demand in a cost-effective way. This however is static and does not conclude on what other renewable sources to integrate over a period of time, given the non-dispatch nature of wind power; it is more suitable as a solution to back-up power.

Lund, 2006, used electrical power minimization to estimate the level of renewables integration for an optimal combination of solar photovoltaic (PV), wind and wave power. Although this approach addresses the important problem of EEP, it says little about the integration of the complementary power needed to satisfy the demand.

Vidal-Amaro et al., 2015, proposed a methodology they called the Minimum Total Mix Capacity (MTMC) for the determination of the optimal mix of renewable energy resources (RES) and fossil fuels in an electricity system by taking into account the hourly values of RES production and electricity demand. They applied this methodology to the Mexican electricity system in a bid

to assess the optimal RES mix that could aid the attainment of a Mexican congressional mandated to limit fossil fuel-based electricity generation be limited to 65% by the year 2024, 60% by 2035 and 50% by 2050. Vidal-Amaro et al., 2015, applied their MTMC model to determine, "...based on actual hourly production values for every RES involved, an optimal energy mix to cover demand using the total RES production share, backup capacity and EEP as optimization criteria". Their methodology, however, focused on maintaining capacities through the assessment of the potential for RES integration into the Mexican electricity and energy source substitution at designated times. Additionally, their data simulation was based on hourly production data. Although this model addressed the optimal energy mix requirements of their study, it does little in addressing the issue on a year-on-year basis and may require said hourly data for the years to be projected; a dataset that is presently not available.

4 Methodology

Our model formulation and procedures have been based on a pure cost analysis and do not include government incentives or subsidies; system balancing costs associated with variable renewables, system-wide cost savings from the merit order, carbon pricing, nor the benefits of renewables in reducing other externalities (e.g. reduced local air pollution, contamination of natural environments, etc.).

Similarly, the benefits of renewables being insulated from volatile fossil fuel prices have not been quantified. The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology. The detailed country level LCOE estimates have been created based on a set of real world data and assumptions that reflect project costs by technology at a single point in time. For clarity purposes, each consideration made in our model formulation of headed to aid ease of reference.

Computation

Computations for this thesis are undertaken with the help of an AMPL IDE version 3.1.0.2. We both lcoe values of the various sources in the AMPL IDE (Appendix I). We also used the AMPL IDE for modeling the LP set of equations and inequalities. We rely on a CPLEX solver, in using the AMPL IDE, for running our model. The results from the AMPL IDE's iterations are then exported into excel for analysis, interpretation and presentation.

Assumptions

1. Availability of LNG regasification plant capable of processing and providing gas for the production of the needed levels of power.
2. Commissioning of all gas resources from Ghana's fields to the production of the needed power.
3. No existing generating facility is decommissioned within the period and hence generation capacities in a given year is greater than or equal to that of the year before.
4. Future energy technologies bear similar technical characteristics as the current technologies and as technological advancements are not factored.

5. The share of renewables (excluding big hydro and nuclear) in the energy mix, beyond 2020 is maintained between 10% and 15%. The 10% being in line with national policy stipulations
6. Nuclear is either built in 335 MW capacity or not built at all unlike modular units which can be built in incremental steps
7. Beside large hydro, all projects are clustered according to its energy source type, this implies homogeneity in energy projects of the same source
8. Interest rate remains unchanged for the plan period (2016 to 2030)
9. Fuel prices are based on long-term contracts and are fixed for the plan period (2016 to 2030)
10. The earliest start for Nuclear development is 2017
11. Given that detailed load curve data is not available as well as the fact that economic and population growth will change the electricity consumption pattern for Ghana in the foreseeable future, we assume that all generation facilities are utilized without any merit order effect. Hence capacity factor is constant throughout the planned period.
12. LCOE is constant throughout the planned period and for each energy source (Implicit assumption from assumptions 4, 8, 9 and 11).

4.1 Energy Source Selection

Energy sources used in in our model where chosen as a result of current GOG policy directions and discussions with industry players. Small/Mini Hydro, Gas, Oil, Wind, Solar and Nuclear where selected for the purposes of this study. Nuclear was selected owing to current GOG considerations. Biomass, though of huge potential and being used by some private individuals to produce some amount of energy (International Renewable Energy Agency, 2015), was omitted owing to current GOG policy direction that focuses on using biofuels mainly in the transportation sector.

4.2 Installed Capacities

Table 4 Installed Generation Capacity (MW) as at 31 December 2015

Plant	Fuel Type	Installed Capacity	Share (%)
Hydro			
Akosombo	Water	1020	27.9
Bui	Water	400	10.9
Kpong	Water	160	4.4
Thermal			
Takiradi Power Company	LCO/Natural Gas	330	9.0
Takoradi International Company	LCO/Natural Gas	330	9.0
Sunon Asogli Power	Natural Gas	200	5.5
Cenin Energy Ltd	LCO	126	3.4
Tema Thermal 1	LCO/Natural Gas	110	3.0
Tema Thermal 2	DFO/Natural Gas	50	1.4
Takoradi 3	LCO/Natural Gas	132	3.6
Mines Reserve Plant	DFO/Natural Gas	80	2.2
Kpone Thermal Power Plant	Natural Gas	220	6.0
Karpowership	HFO	225	6.2
Ameri Plant	Natural Gas	250	6.8
Renewables			
VRA Solar	Solar	2.5	0.1
BXC Company	Solar	20	0.5
Total		3656	100

Source: (Energy Commission of Ghana, 2016)

Additionally, a solar project, the Nzema Solar Project is currently under construction in Ghana and is expected to be the largest solar power installation on the African continent. It is built at a cost of 350 million USD with an installed capacity of 155 MW. Also a wind farm project, the Ayitepa wind farm located in the Ningo-Prampram District (Wind Class 3 Area), is also under construction with an installed capacity of 225 MW. Both projects are expected to be completed and operational in 2017.

Work in Progress (Expected completion 2017)		
Nzema Solar	Solar	155
Ayitepa Wind(Wind Class 3)	Wind	225

4.3 Parameters

4.3.1 Hydro

Akosombo and Kpong are operated as a cascade of hydro plants meaning their electricity production from the two is linked with joint production at total firm average production of 6,000 GWH per annum.

4.3.2 Thermal (Gas & Oil)

At present, Ghana is currently pursuing a track to upgrade all single cycle plants to combined cycle plants. Therefore all plants will be treated as combined cycle plants in the foreseeable future, Ghana’s Gas reserves is expected to come on-stream in 2017 to serve the new thermal plants coming up, thus fuel will be mainly gas. Additionally, the country is currently pursuing the building of a regasification plant to ensure gas can be imported for use if it should be necessary. All indications point to a gas based thermal generation situation. Given the undergoing upgrading in the thermal plants, we will treat all the thermal plants as one unit. The thermal plants can use both crude oil and natural gas. Efficiency in generating electricity is about 44 percent when on crude oil and about 47 percent when on natural gas (Energy Commission of Ghana, 2016).

4.3.3 LCOE parameters

The rapid growth in installed capacity of renewable energy technologies and the associated cost reductions mean that even data one or two years old can significantly overestimate the cost of electricity from renewable energy technologies. The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is a significant barrier to the uptake of these technologies (International Renewable Energy Agency, 2012a).

For technologies like hydro, wind and solar, actual capex is inferred from publicly available sources; while future projects for wind and solar are assumed to have the same capex \$/MW of installed capacity based on the latest wind and solar projects in Ghana, the Nzema Solar plant and Ayitepa wind farm. As Solar PV is modular and there is no lack of space with good radiation in Ghana, we will treat future solar projects as an extension of the Nzema project in terms of parameters.

O&M Costs

Given that actual O&M costs from commissioned projects are not widely available. Even where data are available, care must be taken in extrapolating historical O&M costs given the dramatic changes in renewables technology that have occurred over the last two decades since robust data for the O&M costs has yet to emerge, we infer the O&M cost from Henbest et al., 2015 for Ghana's specific projects and make some plausible assumptions regarding the escalation rates and lifespan regarding the different technologies (Narbel et al., 2014).

Regarding large hydro Annual operations and maintenance costs (O&M) are often quoted as a percentage of the investment cost per kW. Large hydropower projects will typically average around 2% to 2.5%. For large hydropower plants, economic lifetimes are at least 40 years, and 80-year lifetimes can be used as upper bound. For small-scale hydropower plants, the typical lifetime is 40 years but in some cases can be less. The economic design lifetime may differ from actual physical plant lifetimes (International Renewable Energy Agency, 2012b).

Ghana's first Wind farm, the Ayitepa wind farm located 40 kilometers from Accra on the east coast of Ghana, is a 225-MW project representing a total investment of USD 525 million will be expected to supply electricity by 2017. The project lifetime will be 25 years and consist of 75 to 125 Turbines with on average 3MW capacity each and is expected to supply approximately

600,000 MWh per year³ representing a Capex of 2.33 million USD per MW of installed capacity and a capacity factor of 30%. In the United States, data for completed projects suggest that total O&M costs (fixed and variable) have declined from around USD 33/MWh for 24 projects that were completed in the 1980s to USD 22/MWh for 27 projects installed in the 1990s and to USD 10/MWh for the 65 projects installed in the 2000s as the technology matures (International Renewable Energy Agency, 2012a).

A 335 MW nuclear light water reactor (IRIS-335) plant is included in the expansion plan. This small unit nuclear reactor will be financially manageable compared to a 600 MW advanced light water plant, which cost approximately US\$1-1.3 billion to install; about twice the cost of the former. We use a 7 years as the build time for nuclear plants.

Fuel Cost per MWh

The cost of Natural gas is often quoted in USD/MMBtu, the following calculations is used to translate USD/MMBtu to USD/MWh (Narbel et al., 2014), which is the unit used to measure the LCOE. Given the thermal efficiency for gas at $\theta = 47\%$ and since 1 Btu = 1.055 Joules:

Conversion is calculated as follows:

$$\frac{\$}{MMBtu} = Y \times 1.05506 \frac{GJ}{MMBtu}; \text{ Where } Y = \frac{\$}{GJ}$$

The following relationship can be used to estimate how much fuel is needed with a thermal efficiency of 47%.

$$\frac{1}{\theta} \times 3.6 \frac{GJ}{MWH} = 7.66 \frac{GJ}{MWH}$$

This indicates that 7.66 GJ worth of fuel will be needed to generate one MWh of electricity.

$$7.66 \frac{GJ}{MWH} \times \frac{\$}{GJ} = 7.66 \frac{\$}{MWH}$$

³ http://www.upwindayitepa.com/ghana-wind-energy/articles/2015.02.13_Ghanaian_Times.pdf

\$/MMbTU	\$/GJ	\$/MWH
1	0.947813	7.26
2	1.895627	14.52
3	2.84344	21.78
4	3.791254	29.04
5	4.739067	36.30
6	5.68688	43.56
7	6.634694	50.82
8	7.582507	58.08
9	8.530321	65.34
10	9.478134	72.60
11	10.42595	79.86
12	11.37376	87.12
13	12.32157	94.38
14	13.26939	101.64
15	14.2172	108.90

At present average price for long term contracts for Natural Gas is approximately \$9/MMBtu, which translates to a fuel cost of \$65.34 per MWH (Ministry of Petroleum, 2016).

In July 2015, the approx. US \$ cost to get **1 kg of uranium as UO₂ reactor fuel** (at current long-term uranium price):⁴

Uranium:	8.9 kg U₃O₈ x \$97	US\$ 862	46%
Conversion:	7.5 kg U x \$16	US\$ 120	6%
Enrichment:	7.3 SWU x \$82	US\$ 599	32%
Fuel fabrication:	per kg (approx)	US\$ 300	16%
Total, approx:		US\$ 1880	

At 45,000 MWD/t burn-up this gives 360,000 kWh electrical per kg, hence fuel cost: **0.52 ¢/kWh or \$5.20 /MWh**

Rates

In 2015 the Ghanaian Government was able to tap into the International bond market and for the first time issued a Eurobond (\$1 Billion USD) 15-year maturity, making Ghana the first country apart from South Africa in sub-Saharan Africa to issue a bond of such nature, yield to maturity at 2030 were at 10.75%.⁵ Given that there are no bonds issued with a longer timeframe, and it is

⁴ <http://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx>

⁵ <http://em.cbonds.com/countries/Ghana-bond>

not possible to be definitive about discount rates over the lifetime of the project, we will base the long term discount rate at 10.75%.

Table 5 Summary of Energy Supply Parameters

Plants	LCOE	Capex (\$m/MW)	Capacity Factor	Fixed O&M	Fuel Cost \$/MW	Escalation rate %	Lifespan	Current Capacity 2016	Capacity Limit MW	Construction Time (Years)
Thermal	108	1.02	0.75	30,000	58.08	1	25	2053	Nil	2
Small Hydro	52	2.12	0.55	37,000	0	0.5	40	0	800	2
Solar	167	2.26	0.18	45,000	0	0.5	25	22	Nil	1
Hydro_Bui	103	1.98	0.27	49,000	0	0.5	80	400	400	0
Hydro_Ako	52	2.14	0.59	54,000	0	0.5	46	740	1180	0
Wind 3	127	2.33	30%	87,600	0	1	25	0	3575	1
Wind 4	118	2.33	32.5%	87,600	0	1	25	0	1340	1
Wind 5	102	2.33	37.5%	87,600	0	1	25	0	410	1
Wind 6	96	2.33	40%	87,600	0	1	25	0	315	1
Nuclear	114	1.94	0.9	650,000	5.20	1	60	0	335	7

Based on 10.75% interest rates and \$9/MMBtu

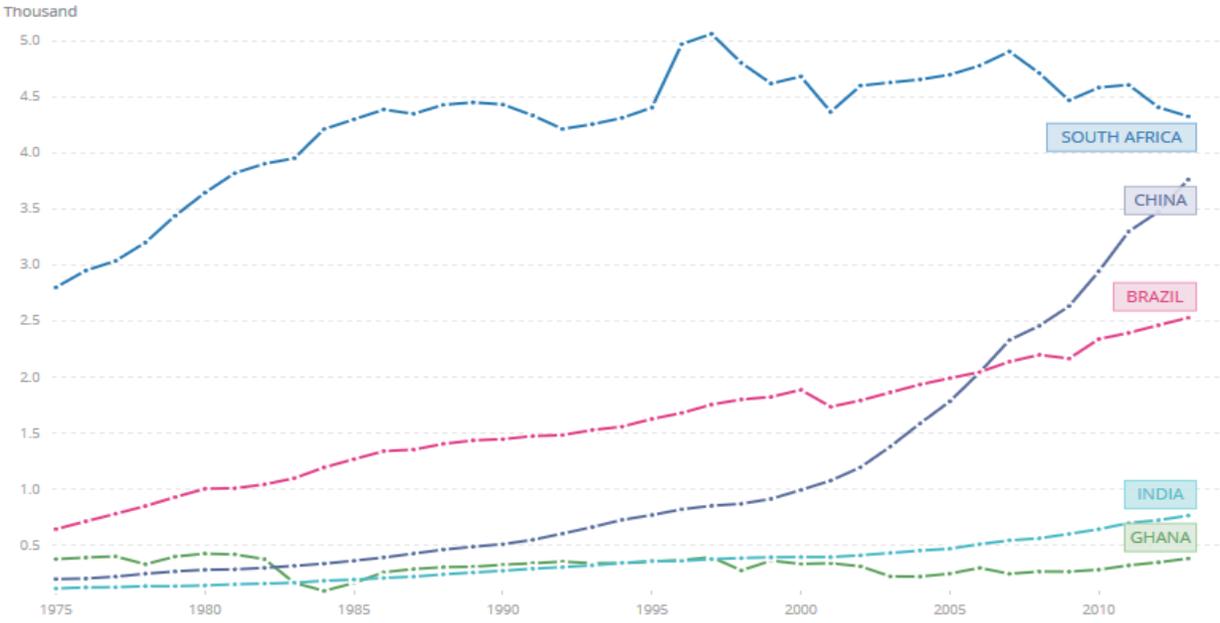
4.3.4 Demand and Year-on-year Demand Growth

Official projections for demand requirements (including transmission and distribution losses), are inferred from the official 2006 to 2020 Strategic National Energy Plan (SNEP) of the Energy Commission of Ghana (Energy Commission - Ghana, 2006). Using projected demand of 27,600 GWH (High Projected Demand Rate) as based demand for 2016 and factoring in a 15% reserve/backup requirement, yields the following projections(to the nearest percent) for 2016-2030.

Table 6 Growth projections - Ghana

Year	Low economic growth	Moderately economic growth	High economic growth
2006-2020	5.29%	8.17%	9.69%
2016-2030	6%	9%	11%

In the high economic growth scenario, an annual growth rate of 9.7% is projected, this is not too far-fetched given that South Africa’s consumption of electricity stands at over 4000 kWh/Capita ; currently the highest in the African continent, while in Ghana it is approximately 400kWh/Capita. Thus it would take about 25 years for Ghana to reach the same levels with a growth rate of 10.2% as an economy's production and consumption of electricity are fundamental indicators of its size and level of development.



Source: World Bank Group – 2016

Figure 13 Electricity consumption per capita for South Africa, China, Brazil, India and Ghana

4.4 Electricity Supply Expansion Plan

Three alternative expansion plans by the Energy Commission of Ghana that have been identified for meeting the supply requirements are (Energy Commission - Ghana, 2006):

1. An expansion plan based primarily on natural gas and with renewable energy (excluding large Hydro) making a 10 percent contribution by installed capacity by 2020.
2. An expansion plan based on natural gas, Bui hydropower project and 10 percent renewable energy (excluding large Hydro) contribution by installed capacity by 2020.
3. An expansion plan based on natural gas, Bui Hydropower project, nuclear power and 10 percent renewable energy contribution (excluding large Hydro) by installed capacity by 2020.

As Bui hydropower project was completed recently, option 1 is negated which leaves options 2 and 3 to investigate. We investigate option 2 with an additional stress scenario. Based on studies done by the EC, due to intermittency and dispatch characteristics a 10 percent contribution of renewable energy (excluding large hydro and nuclear) in the generation mix is the optimum proportion that will maintain the average generation costs of all the options at about the same level (Energy Commission - Ghana, 2006). As such the models will systematically constraint the renewables share of the energy mix per year to 10% to 15% from 2020 onwards.

4.5 Model definition

In line with the theoretical perspectives and literature discussed in this chapter, a linear optimization model is applied to model the essential characteristics of the power challenges facing Ghana. As the population in Ghana increases, the demand for energy is expected to increase exponentially within the next few decades. We define a linear optimization model that relies on the peculiar demand and supply conditions for electricity in Ghana.

The Objective Function

The basic building block of the model will be to simply minimize cost over several time cycles, such as construction cost, operation and management cost, fuel cost across different technologies which are incorporated by the LCOE, while satisfying minimal demand requirement(including

losses and reserves). The decision variables are the amount of capacity install and energy mix for a given basket of energy sources in each year subject to the maximal annual installation potential and renewable portfolio standard constraints , where x_y^p denotes MWH potential per source in year y. Energy generation potential is subjected to the amount of installed capacity allocated to each energy source. In this thesis time cycles or periods are depicted in years. $lcoe_p$ is simply the cost per MWH for each source of energy. An arbitrary large value for Imports (MWH) is used to penalize shortfalls.

$$\text{minimize: } \sum_{p \in P} \sum_{y \in Y} x_y^p \times lcoe_p + \sum_{y \in Y} I_y \times 500$$

Sets

$P = \{\text{Nuclear, Thermal... |P}\}$ set of Power Plants Type

$Y = \{2016, 2017 \dots |2040\}$ set of years

$R = \{\text{Wind3, Wind4 ...|RE}\}$ set of renewable sources excluding large hydro and nuclear

Parameters

$D_y =$ Generation requirement in year y $\forall y \in Y$

$lcoe_p =$ LCOE for power plant type p $\forall p \in P$

$limit_p =$ Installed Capacity (MW) limit for power source p $\forall p \in P$

$IC_p =$ Initial Installed Capacity (MW) for power plant p $\forall p \in P$

$f_p =$ capacity factor for power source p $\forall p \in P$

Decision Variables

$x_{py} =$ Generation Potential (MWH) for power source p in year y $\forall p \in P$ and $y \in Y$

$I_y =$ Imports (MWH) needed in year y $\forall y \in Y$

$z_{py} =$ Installed Capacity (MW) for power source p in year y $\forall p \in P$ and $y \in Y$

$B_y =$ Binary for Nuclear in year y 1 if Nuclear installed capacity = 335MW 0 otherwise $\forall y \in Y$

Constraints

$$z_y^p \leq IC_p \quad \forall p \in P \text{ and } y = 2016$$

Setting the initials conditions, initial installed capacity per energy source in 2016

$$z_y^{\text{Wind3}} \geq 225 \text{ MW } \forall y \in Y \text{ where } y \geq 2017$$

Ayitepa Wind farm is expected to be functional in 2017

$$z_y^{\text{Solar}} \geq 177 \text{ MW } \forall y \in Y \text{ where } = 2017$$

Nzema Solar Plant (155MW + 22MW existing solar =177MW) is expected to be completed in 2017

$$z_y^{\text{Nuclear}} = 0 \text{ MW } \forall y \in Y \text{ where } y \leq 2023$$

As it takes several years for a Nuclear Plant to be completed, it will only be available from 2024 onwards

$$z_y^{\text{Hydro_mini}} = 0 \text{ MW } \forall y \in Y \text{ where } y \leq 2017$$

As it take appromixtately2 years for mini hydro plants to be build

$$z_y^{\text{Thermal}} = 2053 \text{ MW } \forall y \in Y \text{ where } y \leq 2017$$

As it take approximately 2 years for thermal plants to be build; initial install capacity of 2053MW

$$D_y = 27600000 \text{ MWH in } \text{ where } y = 2016$$

Initial base demand requirement

$$D_y = D_{y-1} \times 1.11 \quad y \in Y \text{ where } y \geq 2017$$

Demand growth (includes reserves and losses)

Total generation potential (MWH) of all power plants p in year y has to be greater or equal to demand in year y

$$\sum_{p \in P} x_y^p + I_y \geq D_y \quad \forall y \in Y$$

Installed capacity is greater or equal to the year before, since the timeframe does not include any decommissioning

$$z_y^p \geq z_{y-1}^p \quad \forall p \in P \text{ and } y \in Y, y \geq 2017$$

Generation potential for power plant p in year y cannot exceed maximum installed capacity by a factor of its capacity factor

$$x_y^p \leq \text{limit}_p \times f_p \times 8760 \quad \forall p \in P \text{ and } y \in Y$$

Generation potential for power plant p in year y as a function of installed capacity by a factor of its capacity factor

$$z_y^p \times f_p \times 8760 = x_y^p \quad \forall p \in P \text{ and } y \in Y$$

Nuclear has to have a 335 MW installed capacity otherwise it isn't built, binary $B_y=1$ if nuclear is built 0 otherwise

$$z_y^{Nuclear} \leq B_y \times 335MW \quad \forall y \in Y$$

$$\sum_{p \in P} z_y^r \geq 0.1 \times \sum_{p \in P} z_y^p \quad \forall y \in Y \text{ where } y \geq 2020$$

2020 onwards 10% Renewables target as a fraction of installed capacity excluding large hydro and nuclear

$$\sum_{p \in P} z_y^r \leq 0.15 \times \sum_{p \in P} z_y^p \quad \forall y \in Y \text{ where } y \geq 2020$$

2020 onwards cannot exceed 15% Renewables target as a fraction of installed capacity excluding large hydro and nuclear due to thermal based plan

5 Results and Discussions

In this Chapter we present and discuss our results. We discuss the optimal energy mix for Ghana along with the optimal development path needed for each energy source. We further discuss the resultant year-on-year costs.

5.1 Optimal Mix

The optimal energy mix is illustrated below in Table 7. It shows the path towards the target potential generation capacity at the least cost given actual limitations rather than actual generation, based on an interest rate of 10.75% and actual long term natural gas prices of \$9/MMBtu.

Installed Capacity(MW) \ Years	Hydro_Ako	Hydro_Bui	Hydro_Mini	Nuclear	Solar	Thermal	Wind 3	Wind 4	Wind 5	Wind 6
2016	1180	400	0	0	22	2053	0	0	0	0
2017	1180	400	0	0	177	2053	225	0	0	315
2018	1180	400	394	0	177	3514	225	0	0	315
2019	1180	400	394	0	177	4084	225	0	0	315
2020	1180	400	394	0	177	4716	225	0	0	315
2021	1180	400	503	0	177	5337	225	0	0	315
2022	1180	400	625	0	177	6026	225	0	0	315
2023	1180	400	760	0	177	6791	225	0	0	315
2024	1180	400	800	0	177	7665	225	0	114	315
2025	1180	400	800	0	177	8643	225	0	287	315
2026	1180	400	800	0	177	9764	225	0	410	315
2027	1180	400	800	0	177	11076	225	0	410	315
2028	1180	400	800	0	177	12532	225	0	410	315
2029	1180	400	800	0	177	14149	225	0	410	315
2030	1180	400	800	0	177	15935	227	17	410	315

Table 7 Optimal Energy Mix - Target generation capacity

Table 7 shows the need for a persistent growth in thermal generation over the years, if growing demand is to be met. Some amount of wind energy needs to be developed over the years as well. Hydro generation capacity is to be increased in 2018. However, the national resource potential limitation of 800 MW constrains how far this can go. By 2024, total hydro capacity available is attained and no further increases can be introduced in the hydro space.

Table 8 Optimal Energy Mix (2016 - 2030)

Year \ Source	Hydro	Nuclear	Solar	Thermal	Wind
2016	43%	0%	1%	56%	0%
2017	36%	0%	4%	47%	12%
2018	32%	0%	3%	57%	9%
2019	29%	0%	3%	60%	8%
2020	27%	0%	2%	64%	7%
2021	26%	0%	2%	66%	7%
2022	25%	0%	2%	67%	6%
2023	24%	0%	2%	69%	5%
2024	22%	0%	2%	70%	6%
2025	20%	0%	1%	72%	7%
2026	18%	0%	1%	74%	7%
2027	16%	0%	1%	76%	7%
2028	15%	0%	1%	78%	6%
2029	13%	0%	1%	80%	5%
2030	12%	0%	1%	82%	5%

Table 8 shows what the optimal share of each source should be from 2016 to 2030. The share of thermal energy sources will have to grow from 56% in 2016 to 82% by 2030 (in percentages). This goes to support Ghana's policy inclination towards conventional thermal plants based on natural gas.

We also observe that, in this particular scenario, no nuclear is introduced into the mix. Wind energy initially grows in share by 2017 when the Ayitepa Wind farm comes on line. The share of wind power then declines, despite the coming online of other wind resources as indicated in Table 7. By 2030, wind energy should account for at least 5% of Ghana's energy mix. A similar observation is made for Solar energy. Solar energy will command a 4% share in the energy mix when the Nzema Solar project comes online. However, for optimality, the share of solar energy in the mix declines to 1% by 2025 and remains at 1% till 2030.

A five year period analysis of the optimal mix provides a pictorial overview of the changes in share over the years as presented in Figure 14 below.

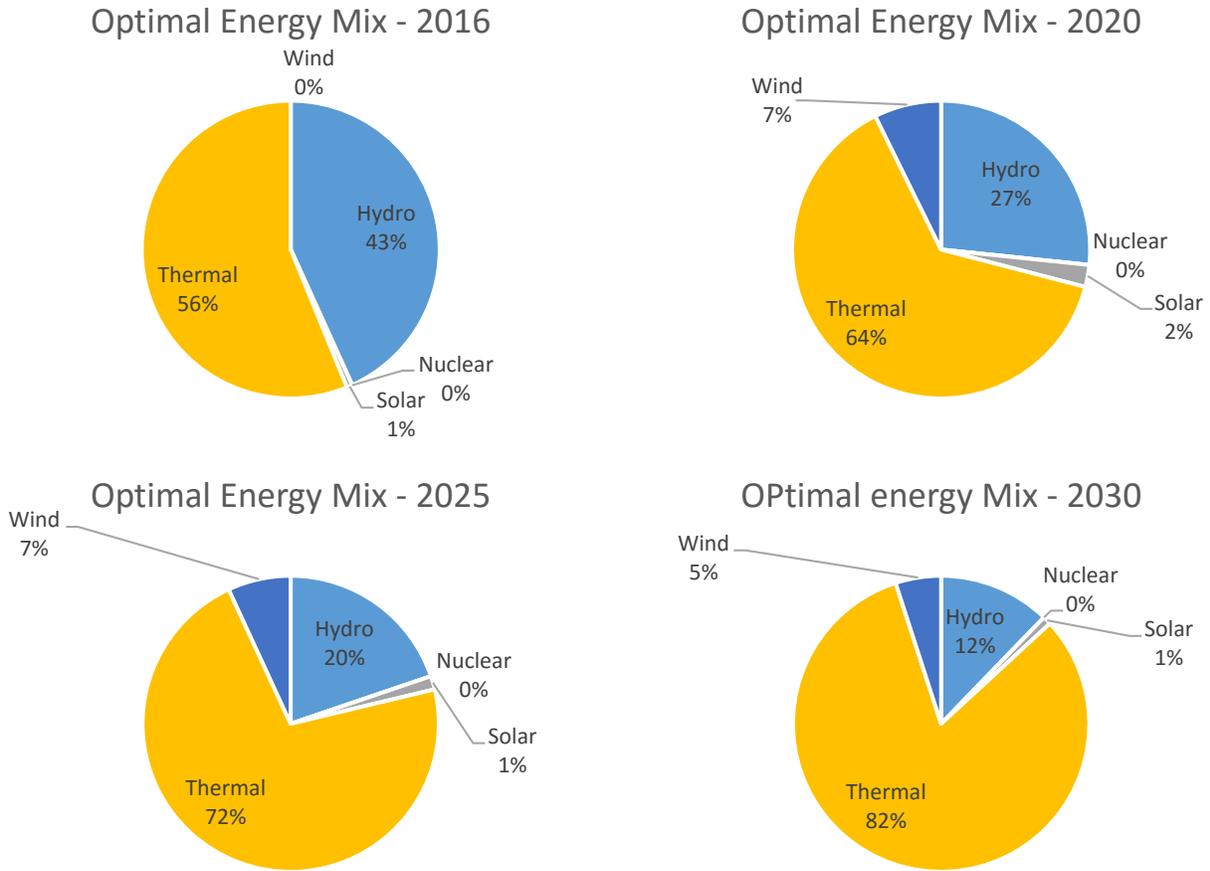


Figure 14 Optimal Energy Mix - 5 year growth starting from 2020 with 2016 as base

Figure 14 shows a pictorial view of the changes in share of optimal energy mix for Wind, Solar, Hydro and Thermal sources from 2016 to 2030 at a 5 year period starting from 2020 with 2016 as the base year. Nuclear remains nonexistent in the current projections.

5.2 Resource development plan

The optimal resource development plan and estimated cost is presented below. The results illustrate that there is no need for the introduction of nuclear technology, as the demand requirement is met. This is also evidenced in the results showing Wind power from Wind Class 4 with no nuclear even though the LCOE for nuclear is lower. Arguments may be raised in favor of introducing nuclear into the mix seeing that the growing demand for energy tends to push the mix towards a mainly thermal one. A few nuclear units may be able to supply enough energy to cater for the growing demand and curtail the continuous need for thermal expansion.

Table 9 Resource development plan for Optimal Energy Mix

Years\Source	Hydro_Mini	Nuclear	Solar	Thermal	Wind 3	Wind 4	Wind 5	Wind 6
2016	394	0	155	1461	225	0	0	315
2017	0	0	0	570	0	0	0	0
2018	0	0	0	632	0	0	0	0
2019	109	0	0	621	0	0	0	0
2020	122	0	0	689	0	0	0	0
2021	135	0	0	765	0	0	0	0
2022	40	0	0	874	0	0	0	0
2023	0	0	0	978	0	0	114	0
2024	0	0	0	1121	0	0	173	0
2025	0	0	0	1312	0	0	123	0
2026	0	0	0	1456	0	0	0	0
2027	0	0	0	1617	0	0	0	0
2028	0	0	0	1786	0	0	0	0
2029	0	0	0	0	2	17	0	0
2030	0	0	0	0	0	0	0	0

Table 9 shows the optimal resource development plan for meeting year on year growth in energy demand. The plan factors-in the build period for each of the sources in order for the needed energy to be available for use in the year of need.

The plan shows that some amount of investment into plant expansion should currently be ongoing. There should be, at least, 1,461 MW thermal capacity expansion, 394 MW mini-hydro expansion, and 315 MW additional wind energy capacity expansion. Wind Class 3 and Solar already have 225 MW and 155 MW already underway. Any shortfall in these values or in any other year as presented in the optimal resource development plan, *ceteris paribus*, will lead to the insurgence of a power crisis with the resulting;

- a. need for electricity to import electricity from the neighboring countries or
- b. load-shedding

As indicated earlier, thermal sources seem to be the dominant source to be relied upon. In 2016, GOG signed two thermal power deals (Ameri Power – 250 MW and Karpower 400 MW) for the supply of 700 MW of power. These additions will bring the net necessary values for 2016 to 761 MW of additional thermal capacity to be invested into to ensure demand in subsequent years.

Table 10 Resource development cost (\$m/MW)

Year\Source	Hydro_Mini	Nuclear	Solar	Thermal	Wind 3	Wind 4	Wind 5	Wind 6	Total
2016	835.28	0	350.3	1490.22	524.25	0	0	733.95	3,934.00
2017	0	0	0	581.4	0	0	0	0	581.40
2018	0	0	0	644.64	0	0	0	0	644.64
2019	231.08	0	0	633.42	0	0	0	0	864.50
2020	258.64	0	0	702.78	0	0	0	0	961.42
2021	286.2	0	0	780.3	0	0	0	0	1,066.50
2022	84.8	0	0	891.48	0	0	0	0	976.28
2023	0	0	0	997.56	0	0	265.62	0	1,263.18
2024	0	0	0	1143.42	0	0	403.09	0	1,546.51
2025	0	0	0	1338.24	0	0	286.59	0	1,624.83
2026	0	0	0	1485.12	0	0	0	0	1,485.12
2027	0	0	0	1649.34	0	0	0	0	1,649.34
2028	0	0	0	1821.72	0	0	0	0	1,821.72
2029	0	0	0	0	4.66	39.61	0	0	44.27
2030	0	0	0	0	0	0	0	0	0

Table 10 above show the projected resource development costs for each source and for each year in US dollars per megawatt, calculated by proposed installed capacity multiplied by \$/MW in table 5. The data indicates that huge investments are needed in 2016 in order to meet demand at the subsequent years. Investment of almost \$ 4 billion is needed in capacity expansion in order to meet growing energy demand of the subsequent years and ensure economic growth is not stifled. In the subsequent years, less intensive investment requirements are recorded. However, from the year 2021 till 2029, annual investment requirements for capacity expansion averages approximately \$ 1.4 billion.

The situation in 2016 is not really surprising considering the fact that Ghana's has infrastructural challenges in its energy sector. Challenges that haven't compounded over the years. Addressing these challenges now for a secure electricity supply future therefore requires a level of investment capable of bringing systems at par with current demand trends.

5.3 Sensitivity Analysis

Without access to reliable information on the relative costs and benefits of renewable energy technologies, it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances. The rapid growth in installed capacity of renewable energy technologies and the associated cost reductions mean that even data one or two years old can significantly overestimate the cost of electricity from renewable energy technologies. The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is a significant barrier to the uptake of these technologies (International Renewable Energy Agency, 2012a).

Levelized Cost of Electricity (LCOE) and its limitations

Levelized cost of electricity (LCOE) although the most convenient measure of the overall competitiveness of different generating technologies, the importance of the factors varies among the technologies. For technologies such as solar and wind generation that have no fuel costs and relatively small variable O&M costs, LCOE changes in rough proportion to the estimated capital cost of generation capacity. For technologies with significant fuel cost, fuel cost estimates significantly affect LCOE. As such, there is uncertainty about all of these factors and their values can vary regionally and across time as technologies evolve and fuel prices change. Basing decisions on LCOE alone can lead to over and under investment. The capacity factor, which depends on the load shape and the existing resource mix in an area where additional capacity is needed, can also affect estimates significantly (U.S Energy Information Administration, 2016).

Since load must be balanced on a continuous basis, units whose output can be varied to follow demand (dispatchable technologies) generally have more value to a system than less flexible units (non-dispatchable technologies), or those whose operation is tied to the availability of an intermittent resource. With Ghana being a developing country, the load curve is expected to change dramatically, hence our model did not take into account generation cost, and is also in line with the Ghana's energy policy direction of building up potential generation capacity at the lowest cost rather than including merit order dispatch and intermittency issues. Also no load curve data is available and studies of integration of renewables into Ghana's electricity supply

systems has not been done hence no data about generation cost can be accurately calculated. Since projected utilization rates, the existing resource mix, and capacity values can all vary dramatically across regions where new generation capacity may be needed, the direct comparison of LCOE across technologies is often problematic and can be misleading as a method to assess the economic competitiveness of various generation alternatives.

Table 11 LCOE values of energy sources at various rates

Source \ Rates	Hydro_Ako	Hydro_Bui	Hydro_Mini	Nuclear	Solar	Wind 3	Wind 4	Wind 5	Wind 6	Thermal (\$9/MMbTU)
4.75%	32	61	32	109	106	90	83	72	68	103
6.75%	38	74	38	109	125	102	94	81	76	104
8.75%	45	89	45	111	145	114	105	91	86	106
10.75%	52	103	52	114	167	127	118	102	96	108
12.75%	59	118	60	117	189	141	131	113	106	109
14.75%	66	133	67	120	213	156	144	125	117	111
16.75%	74	148	75	124	237	171	158	137	128	114

Table 11 shows LCOE values for the various energy sources at various interest rates. We observe that as the rates increases, the LCOE of the various sources increases as well. Figure 15 presents

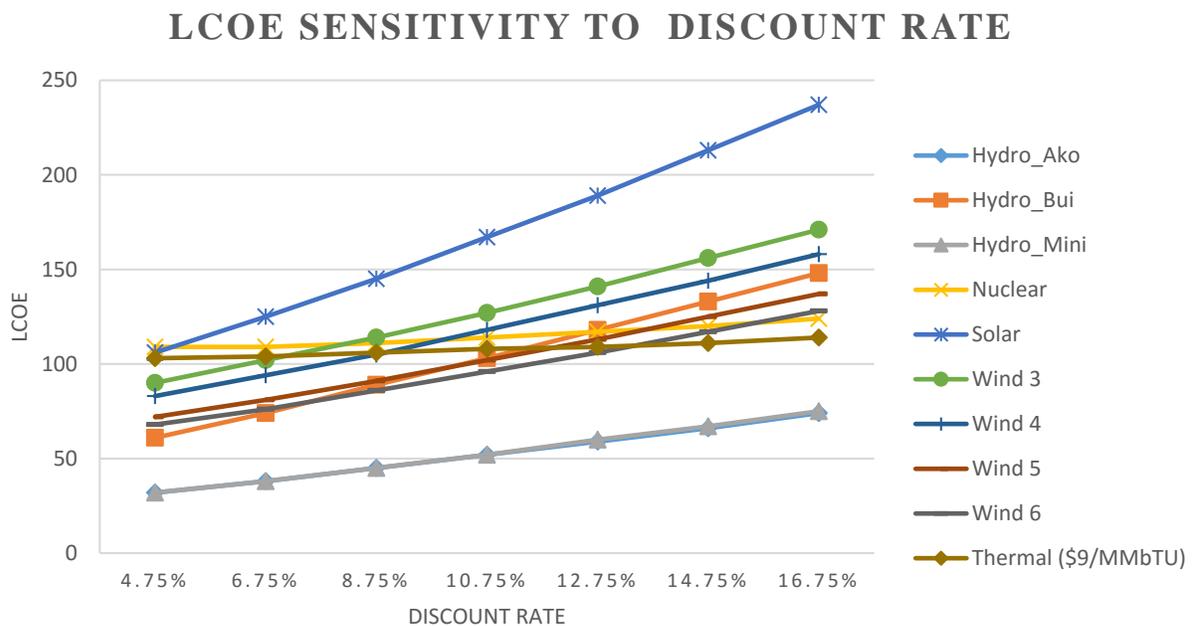


Figure 15 Energy Source LCOE sensitivity to discount rates

a graphical view of this.

As can be seen from Figure 15, Solar is most sensitive to interest rates, while Thermal is most sensitive to fuel price changes (Risto and Aija, 2008). With the resource development plan being on Thermal, we investigate the optimal mix in a high fuel price (\$15/MW) and interest rate (16.75) stress environment. The result shows that in a high fuel price and interest rate environment, Nuclear power needs to be introduced into the mix.

Table 12 Resource capacity plan in a stressed environment (High interest rate coupled with high fuel cost)

Year\Source	Hydro_Ako	Hydro_Bui	Hydro_Mini	Nuclear	Solar	Thermal	Wind 3	Wind 4	Wind 5	Wind 6
2016	1180	400	0	0	22	2053	0	0	0	0
2017	1180	400	0	0	177	2053	225	0	0	134
2018	1180	400	569	0	177	3482	225	0	0	134
2019	1180	400	569	0	177	4052	225	0	0	134
2020	1180	400	569	0	177	4684	225	0	0	134
2021	1180	400	678	0	177	5305	225	0	0	134
2022	1180	400	800	0	177	5994	225	0	0	134
2023	1180	400	800	0	177	6784	225	0	0	274
2024	1180	400	800	335	177	7268	225	0	103	315
2025	1180	400	800	335	177	8247	225	3	273	315
2026	1180	400	800	335	177	9336	225	58	410	315
2027	1180	400	800	335	177	10555	225	273	410	315
2028	1180	400	800	335	177	11908	225	512	410	315
2029	1180	400	800	335	177	13410	225	777	410	315
2030	1180	400	800	335	177	15077	225	1071	410	315

Table 12 shows an increase in the hydro capacity requirement in 2018 as compared to that of the optimal capacity plan in Table 7. It is also observed that there is the need for rapid development of hydro resources in the stressed environment than there is under the optimal capacity plan in Table 7. Hydro resources tend to be exhausted by 2022 rather than 2024 (as in the optimal development plan). Evidently, the introduction of Nuclear, under such stress circumstances results in a significant changes in the optimal energy mix as presented below;

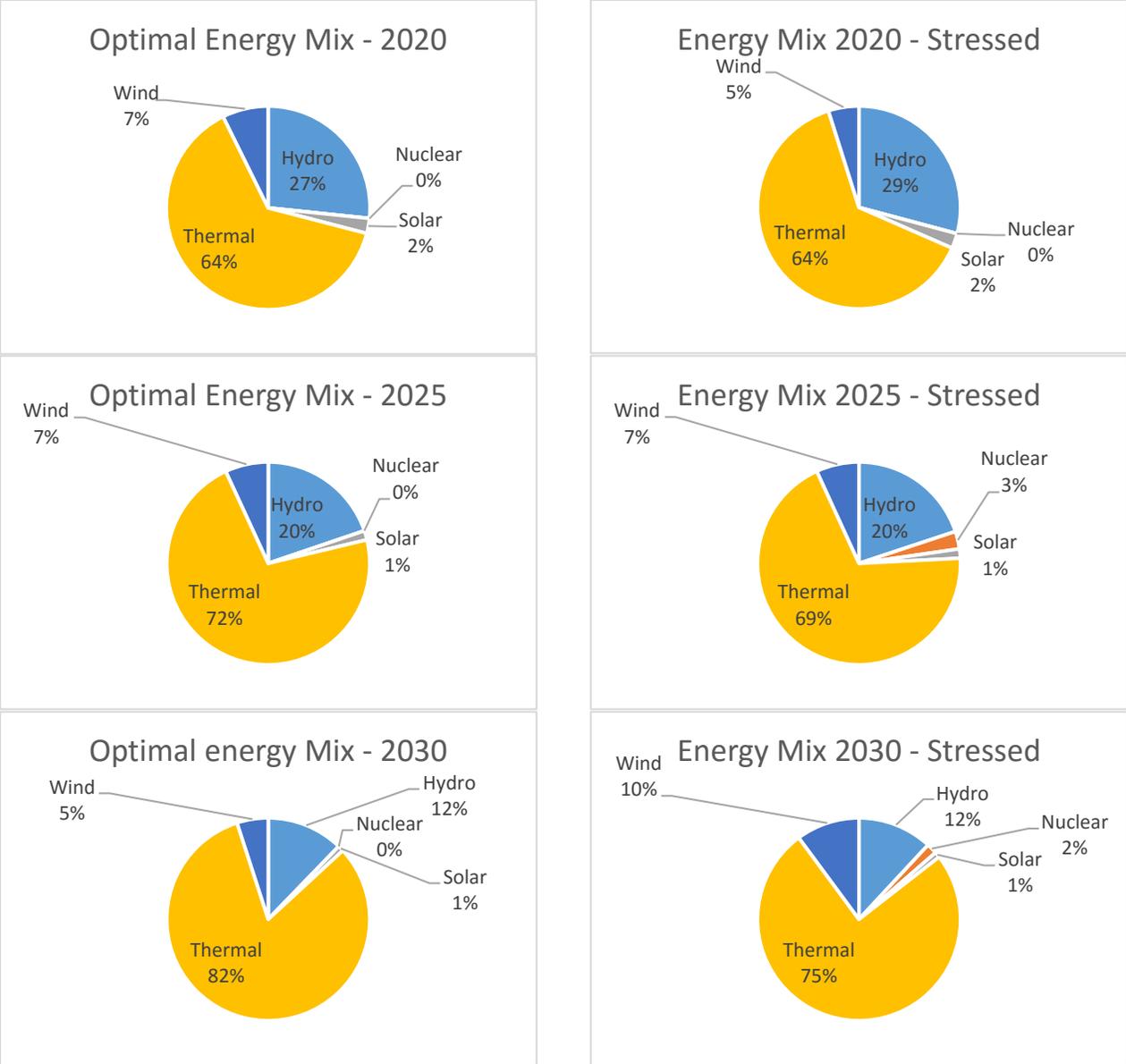


Figure 16 Comparative view of Optimal Energy Mix and Energy Mix in stressed environment (2020, 2025 and 2030)

From Figure 16 above, hydro sources maintain their share in the energy mix irrespective of the stress situation. Wind energy gets a boost in the stressed situation and needs to be maintained at 10% by 2030. Thermal energy sources take the greatest hit with a 7% reduction in share of energy mix; reflecting the sensitivity of Thermal power generation to the stress parameters introduced. Nuclear energy finally gets a 3% share by 2025. This falls to 2%, mainly owing to the constraints of the model. The resource development path also tends to differ from the that of the optimal energy mix situation. This is captured in Table 13 below;

Table 13 Resource Development Path - Stressed Scenario 2016 - 2030

Year\Source	Hydro_Mini	Nuclear	Solar	Thermal	Wind 3	Wind 4	Wind 5	Wind 6
2016	569	0	155	1429	225	0	0	134
2017	0	335	0	570	0	0	0	0
2018	0	0	0	632	0	0	0	0
2019	109	0	0	621	0	0	0	0
2020	122	0	0	689	0	0	0	0
2021	0	0	0	790	0	0	0	0
2022	0	0	0	484	0	0	0	140
2023	0	0	0	979	0	0	103	41
2024	0	0	0	1089	0	3	170	0
2025	0	0	0	1219	0	55	137	0
2026	0	0	0	1353	0	215	0	0
2027	0	0	0	1502	0	239	0	0
2028	0	0	0	1667	0	265	0	0
2029	0	0	0	0	0	294	0	0
2030	0	0	0	0	0	0	0	0

Per Table 13 above, a lot more Wind resources will have to be developed over the years with a corresponding reduction in Thermal energy. Solar resources are not developed at all. Nuclear gets introduced and its construction needs to be commenced by 2017 in order for its power to be available by 2024.

The stressed scenario so described and analyzed may seem extreme but this is rather not so far from the realities for a developing country like Ghana. This is because, despite being an oil drilling country, Ghana is still largely a price taker for fuel. Additionally, interest rate trends and current bond prices indicate that a 16.75% rate is not too far off. Such stress scenarios are very likely despite the current price of fuel.

5.4 Meeting the Optimal Energy Mix

The optimal energy mix and development path provides us with an idea of which energy sources need to be developed and at which rate. The associated capital expenditure, *ceteris paribus*, provides us with a fair value assessment of what investments need to be undertaken per annum in order for growing annual energy demand to be met. We briefly discuss the each of the sources;

5.4.1 Hydro

The optimal resource development path indicates the development of Ghana's hydro resource in the years 2016, 2019, 2020 and 2021. By the year 2021, all hydro resources, in the form of small and mini- hydro dams should be developed. According to International Renewable Energy Agency, 2015, feasibility studies for the development of these sites are currently being carried out by the VRA. Ghana currently has enough knowhow in the management of hydro dams and with the appropriate investment, these dams should be able to come online at the appropriate time. Data on the sites and their respective capacities is amply available (International Renewable Energy Agency, 2015).

5.4.2 Solar

The optimal energy mix does not add solar development for the period aside from taking cognizance of the 155 MW that's to come online in 2017. This situation may be as a result of the high lcoe of solar. This is owing to the fact that the model sought to minimize cost. However, solar energy is one energy form that Ghana may tap much energy from. With the current solar irradiation records indicating an energy yield from existing solar technologies to be a daily average between 4 kWh to 6 kWh across the nation, most households could source their daily electrical energy needs by solar. This could avail much need grid power and lower the investment needs for power supply.

The problem with solar technology uptake is usually the initial cost (Willis, 2012). This is a major problem for Ghana were incomes are low. In the face of the ongoing energy crisis, a number of middle class households have resorted to securing solar technology for the provision of the needed energy. In a bid to improve the uptake of solar as an option for household power

production, GOG can actively promote distributed generation schemes by promoting solar technology through incentives in the form of subsidies, tax cuts or the introduction of net metering. Additionally, Ghana can pursue, on a large scale, public-private-partnerships aimed at producing the technology components for harvesting solar energy in Ghana. This will positively reduce the cost of acquiring the technology simply through the economies of scale and the elimination of importation taxes.

Pursuing local solar energy technology component production coupled with incentives will improve the grid electricity supply deficit situation as uptake picks up. The effect will be a reduction in the need for massive investments for the supply of power.

5.4.3 Thermal (Oil and Gas)

Ghana is expecting the inflow of huge volumes of gas from its oil and gas fields and this has been earmarked for power generation. It is expected that this gas will be used to power the thermal systems to be developed as per the optimal energy mix.

In following the optimal resource development path, huge investments are needed annually for the provision of the capacities indicated. The reliance on Thermal, therefore indicates that, *ceteris paribus*, any shortfall in investments for the provision of these capacities will lead to a possible shortfall in supply of electricity. Despite this being true for all the resources within the optimal energy mix, the trend of development needed for Thermal makes the Thermal component of the energy mix rather critical. Additionally, Thermal systems may be the most flexible and large scale ready-to-go power supply systems that can be relied upon for emergency power provision. Much effort needs to be made in ensuring the appropriate investment is made to ensure the realizing of the Thermal needs, as with the other sources.

5.4.4 Wind

The optimal energy mix requires for the development of Wind Class 6 resources to commence in 2016, Wind Class 5 in 2023 through to 2025 and Wind Class 4 resources in 2029. Owing to the relatively high lcoe of Wind energy (compared to Thermal), not much of wind resources are recommended for development despite an over 5000 MW identified potential that can be tapped.

This notwithstanding, any development of wind resources in parallel with the optimal energy mix will be advantageous in reducing the investment needs for meeting growing energy demand.

6 Conclusion and Recommendations

6.1 Conclusion

Overall, the model developed in this thesis provided us with an optimal energy mix for the eradication of periodic power crisis in Ghana from 2016 till 2030. It therefore offers a useful framework for further studies and research into the optimal energy mix for developing countries. The model also helped us develop an optimal resource development path for the development of energy resources available to the nation, over the period 2016. It provided an avenue for further calculating the associated capital expenditure for the optimal resource development path developed. The inclusion of Nuclear energy in this model (in addition to local energy sources) afforded an opportunity for the meeting of growing energy demand in diverse stress considerations, though the optimal energy mix did not factor nuclear in the optimal mix.

Despite the compelling arguments that may be raised in defense of going nuclear (Goldemberg, 2009), our model, under the constraints as indicated in national policy and strategy documents of Ghana, *ceteris paribus*, indicates that optimally, Ghana can do without the nuclear option for now. However, under stress conditions such as increased interest rates and high fuel prices per MW, nuclear becomes an attractive option. The nuclear argument may be driven by numerous factors outside the scope of this thesis. One of these may be environmental conditions like the current trends in climate change. As Linrterud et al., 2011, notes “A warmer climate may result in lower thermal efficiency and reduced load – including shutdowns – in thermal power plants.”; a situation that will favor the Nuclear option in the face of exhaustion of reliable potential renewable energy sources.

Our results also indicates that huge investment opportunities exist in the energy sector of Ghana. With annual optimal capital expenditure necessary for the supply of the needed power to meet growing annual energy demand averaging \$1 billion, Ghana requires serious investment in the energy sector. Additionally, Ghana is a politically stable country with solid democratic credentials; a good combination for investors seeking good returns on their investments.

The results of this thesis indicates that, Ghana needs to action a long-term plan aimed at annual development and introduction of national energy resources in a sustained manner. This year-on-year development should be aimed at not only meeting current energy demands but be sufficient enough to factor in energy demands of the subsequent years.

6.2 Recommendations

Techno-Spread and Geographical Dispersion

The quality and quantity of sunlight hours is consistent throughout the year, since wind, solar radiation, waves and tides are not all correlated with spatial dispersion there could be a possibility of reducing the intermittency exposure by combining multiple intermittent energy technologies, it solidifies the portfolio of energy mix which may reduce the need for back up capacity as these technologies may be complementary. Such type of diversification can be referred to as ‘techno-spread’(OECD Nuclear Energy Agency, 1986). As there is little or no data on such spatial correlation, it is therefore recommended that data on the research area regarding spatial correlation of the renewable energy sources in Ghana could be carried out.

Grid Impact

Additionally managing reactive power compensation is critical to grid stability, making the transition to large-scale renewable energy supply requires substantial shifts in infrastructure: grid modernization, adoption of new technologies, reworked business models for utilities, and updated policy and regulatory frameworks.

Ghana’s total installed electricity generation capacity presently is about 3,656 MW, increasing install capacity at an exponential pace too soon within such a small grid could create instabilities in the operation of the national electrical system. Tapping into renewables may require additional investment in the existing grid usually at a great cost; location consideration does make a difference especially if a local grid can suffice to provide residents with electricity. We recommend further research in this area in support of the needed expansion in capacities and actual power production to meet growing energy demand.

7 Bibliography

- Branker, K., Pathak, M., and Pearce, J.M. (2011). A review of solar photovoltaic levelized cost of electricity. *Renew. Sustain. Energy Rev.* *15*, 4470–4482.
- Brew-Hammond, A., and Kemausuor, F. (2007). *Energy Crisis in Ghana: Drought, Technology Or Policy?* (Kwame Nkrumah University of Science and Technology, College of Engineering).
- Brunnschweiler, C.N. (2010). Finance for renewable energy: an empirical analysis of developing and transition economies. *Environ. Dev. Econ.* *15*, 241–274.
- Dantzig, G.B., and Thapa, M.N. (2006). *Linear programming 1: introduction* (Springer Science & Business Media).
- De Jonghe, C., Delarue, E., Belmans, R., and D’haeseleer, W. (2011). Determining optimal electricity technology mix with high level of wind power penetration. *Appl. Energy* *88*, 2231–2238.
- Dixit, A.K., and Pindyck, R.S. (1994). *Investment under uncertainty* (Princeton university press).
- Duku, M.H., Gu, S., and Hagan, E.B. (2011). A comprehensive review of biomass resources and biofuels potential in Ghana. *Renew. Sustain. Energy Rev.* *15*, 404–415.
- Energy Commission - Ghana (2005). *SWERA - National Report*.
- Energy Commission - Ghana (2006). *Strategic National Energy Plan (2006-2020)*.
- Energy Commission - Ghana (2016). *2016 Energy (Demand and Supply) Outlook for Ghana*.
- Energy Commission of Ghana (2016). *National Energy Statistics - 2015*.
- Fernandes, B., Cunha, J., and Ferreira, P. (2011). The use of real options approach in energy sector investments. *Renew. Sustain. Energy Rev.* *15*, 4491–4497.
- Goldemberg, J. (2009). Nuclear energy in developing countries. *Daedalus* *138*, 71–80.
- Government of Ghana (2012). *Ghana Sustainable Energy for All Action Plan*.
- Gyamfi, S., Modjinou, M., and Djordjevic, S. (2015). Improving electricity supply security in Ghana—The potential of renewable energy. *Renew. Sustain. Energy Rev.* *43*, 1035–1045.
- Henbest, S., Mills, L., Orlandi, I., Serhal, A., and Pathania, R. (2015). *Levelised Cost of Electricity: DFID 28 priority countries*.
- Iddrisu, I., and Bhattacharyya, S.C. (2015). Ghana's bioenergy policy: Is 20% biofuel integration achievable by 2030? *Renew. Sustain. Energy Rev.* *43*, 32–39.

- International Renewable Energy Agency (2012a). Renewable Energy Technologies: Wind Power Cost Analysis Series. Int. Renew. Energy Agency.
- International Renewable Energy Agency (2012b). Renewables Technology Series: Hydro Power Cost Analysis Series. Int. Renew. Energy Agency.
- International Renewable Energy Agency (2015). Ghana Renewables Readiness Assessment.
- IPCC (2011). Renewable energy sources and climate change mitigation (Potsdam Institute for Climate Impact Research (PIK)).
- Karekezi, S., and Kithyoma, W. (2006). Bioenergy and the Poor. *Bioenergy Agric. Promises Chall.* 2020.
- Kastning, T. (2016). Basic Overview of Ghana's Emerging Oil Industry.
- Kemausuor, F., Obeng, G.Y., Brew-Hammond, A., and Duker, A. (2011). A review of trends, policies and plans for increasing energy access in Ghana. *Renew. Sustain. Energy Rev.* 15, 5143–5154.
- Linrterud, K., Mideksa, T.K., and Eskeland, G.S. (2011). The impact of climate change on nuclear power supply. *Energy J.* 32, 1.
- Lund, H. (2006). Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. *Renew. Energy* 31, 503–515.
- Mathrani, S., Santley, D., Hosier, R., Bertholet, F., Braud, A., Dawson-Amoah, G., and Reinoso, G. (2013). Energizing economic growth in Ghana: Making the power and petroleum sectors rise to the challenge. Wash. DC.
- Mensah, J.T., Marbuah, G., and Amoah, A. (2016). Energy demand in Ghana: A disaggregated analysis. *Renew. Sustain. Energy Rev.* 53, 924–935.
- Ministry of Energy (2010a). Energy Sector Strategy and Development Plan.
- Ministry of Energy (2010b). National Energy Policy.
- Ministry of Petroleum (2016). Gas Master Plan.
- Ministry of Power (2015). Scaling-up Renewable Energy Program in Ghana (SREP): Investment Plan.
- Narbel, P.A., Hansen, J.P., and Lien, J.R. (2014). *Energy technologies and economics* (Springer).
- OECD Nuclear Energy Agency (1986). Projected Costs of Generating Electricity.
- Østergaard, P.A. (2009). Reviewing optimisation criteria for energy systems analyses of renewable energy integration. *Energy* 34, 1236–1245.

- Quist, E. (2016). VRA Debt: List of VRA's debt to 13 banks.
- Resource Centre for Energy Economics and Regulation, Legon (2005). Guide to Electric Power in Ghana (Resource Centre for Energy Economics and Regulation, Legon).
- Risto, T., and Aija, K. (2008). Comparison of electricity generation costs. 20.
- Roth, I.F., and Ambs, L.L. (2004). Incorporating externalities into a full cost approach to electric power generation life-cycle costing. *Energy* 29, 2125–2144.
- Saeko, S., Ryoichi, R.K., and Yasumasa, F. (2010). Evaluation of the Optimal Power Generation Mix with Regional Power Interchange considering Output Fluctuation of Photovoltaic System and Wind Power Generation.
- Schillings, C., Meyer, R., and Trieb, F. (2004). Solar and Wind Energy Resource Assessment (SWERA) - High Resolution Solar Radiation Assessment for Ghana.
- Short, W., Packey, D.J., and Holt, T. (1995). A manual for the economic evaluation of energy efficiency and renewable energy technologies.
- Sickles, R. (2008). Energy Economics. In *The New Palgrave Dictionary of Economics*, S.N. Durlauf, and L.E. Blume, eds. (Basingstoke: Nature Publishing Group), pp. 842–848.
- Sweeney, J.L. (2002). Energy Economics.
- The Secretary-General's High-Level Group on Sustainable Energy for All (2012). Sustainable Energy for All - A Global Action Agenda: Pathways for Concerted Action towards Sustainable Energy for All.
- U.S Energy Information Administration (2016). Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016.
- U.S National Renewable Energy Laboratory (2002). Technical Report - Ghana Wind Energy Resource.
- Verbong, G.P., and Geels, F.W. (2010). Exploring sustainability transitions in the electricity sector with socio-technical pathways. *Technol. Forecast. Soc. Change* 77, 1214–1221.
- Vidal-Amaro, J.J., Østergaard, P.A., and Sheinbaum-Pardo, C. (2015). Optimal energy mix for transitioning from fossil fuels to renewable energy sources—The case of the Mexican electricity system. *Appl. Energy* 150, 80–96.
- Weisstein, E.W. (2006). Simplex Method.
- Willis (2012). Poll: Costs discouraging energy efficiency adoption.
- Yergin, D. (2006). Ensuring energy security. *Foreign Aff.* 69–82.

8 Appendix I

8.1 Model – Scenario 1 (Expansion plan option 2)

```
#sets#
set P; # set of Power Plants
set Y; #Year
set R; #Renewables

#####
#Parameters#

var D{Y};#Demand
param lcoe{P};#
param limit{P};#Capacity Limitation
param f{P};#capacity factor
param IC{P};#Initial installed capacity

#decision variables#

var x{P,Y} >=0; #MWH potential by power source p in year y
var z{P,Y}integer >=0; #installed capacity in MW power source p in year y
var I{Y} >=0; #imports(MWH) in year y
var B{Y} binary;#Binary =1 if 335MW of Nuclear is installed else 0

#####
#objective funtion to minimize cost#

minimize Cost:
sum {p in P,y in Y}lcoe[p]*x[p,y] +sum{y in Y} I[y] *500; #cost

subject to

#Initial Conditions
constraint1{p in P}:z[p,2016]<=IC[p];#Initial installed capacity
constraint3{y in Y:y>=2017}:z["Wind3",y]>=225; #Ayitepa comes unto the Grid
constraint4:z["Solar",2017]>=177; #Nezema comes unto the Grid
constraint5{y in Y:y<=2023}:z["Nuclear",y]=0; #Nuclear only possible from 2024
onwards
constraint6{y in Y:y<=2017}:z["Hydro_mini",y]=0; #Mini_Hydro constuction time 2 years
constraint7{y in Y:y<=2017}:z["Thermal",y]=2053; #Thermal constuction time 2 years

#demand Constraints
constraint8: D[2016]=27600000; #base demand MWH
constraint9{y in Y:y>=2017}: D[y]=D[y-1]*1.11; # demand growth
constraint10{y in Y}: sum {p in P} x[p,y]+ I[y]>=D[y]; #Total generation + imports in
year y= demand in year y (MWH)

#Operational Constraints
```

```

constraint11{p in P,y in Y:y>=2017}: z[p,y] >=z[p,y-1]; # Installed capacity
continuity
constraint12{p in P,y in Y}: x[p,y] <=limit[p]*8760*f[p]; # Generation limit
constraint13{p in P,y in Y}: z[p,y]*8760*f[p] =x[p,y]; # Generation as a function of
Installed capacity
constraint14{y in Y}:z["Nuclear",y] =335*B[y];#Binary =1 if 335MW of Nuclear is
installed else 0
constraint15{y in Y:y>=2020}:sum {r in R} z[r,y] >=0.1*sum {p in P} z[p,y];#2020 10%
Renewables target excluding large Hydro
constraint16{y in Y:y>=2020}:sum {r in R} z[r,y] <=0.15*sum {p in P} z[p,y];#2020 15%
max cap on Renewables target excluding large Hydro

```

8.2 Data

```

set P:= Wind3 Wind4 Wind5 Wind6 Solar Hydro_Bui Hydro_Ako_Kpong Hydro_mini Thermal
Nuclear; #Set of power plants
set R:= Wind3 Wind4 Wind5 Wind6 Solar Hydro_mini ; #set of Renewables Source
exclduing large Hydro
set Y:= 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029
2030;#year

```

param:	lcoe	limit	f	IC	:=
Wind3	127	3575	0.3	0	
Wind4	118	1340	0.325	0	
Wind5	102	410	0.375	0	
Wind6	96	315	0.4	0	
Solar	167	999999	0.18	22	
Hydro_Bui	103	400	0.27	400	
Hydro_Ako_Kpong	52	1180	0.59	1180	
Hydro_mini	52	800	0.55	0	
Thermal	108	9999999	0.75	2053	
Nuclear	114	335	0.9	0	;

8.3 Model – Scenario 2

Interest rate at 16.75% and fuel price at \$15/MW

8.4 Data

```
set P:= Wind3 Wind4 Wind5 Wind6 Solar Hydro_Bui Hydro_Ako_Kpong Hydro_mini Thermal
Nuclear; #Set of power plants
set R:= Wind3 Wind4 Wind5 Wind6 Solar Hydro_mini ; #set of Renewables Source
exclduing large Hydro
set Y:= 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029
2030;#year
```

param:	lcoe	limit	f	IC	:=
Wind3	171	3575	0.3	0	
Wind4	158	1340	0.325	0	
Wind5	137	410	0.375	0	
Wind6	128	315	0.4	0	
Solar	237	999999	0.18	22	
Hydro_Bui	148	400	0.27	400	
Hydro_Ako_Kpong	74	1180	0.59	1180	
Hydro_mini	75	800	0.55	0	
Thermal	170	9999999	0.75	2053	
Nuclear	124	335	0.9	0	;

8.5 LCOE Calculator – Model

```

#sets#
set P; # set of Power Plants

#####
#Parameters#

param T{P};#Plant Life
param r;#discount rate
param H;#hours per year
param cp{P};#capital cost
param f{P};#capacity factor
param om{P};#operating and maintenance cost
param e{P};#esclation rate
param fuel{P}; #fuel cost

var R{P}>=0;
var Capital_Cost{P}>=0;
var l{P}>=0;
var lcoe{P}integer >=0;

#Decision Variables#

#####
#objective funtion to minimize cost#

minimize Cost:
1+1;

subject to
constraint1{p in P}:R[p]= r*(1+r)^T[p]/((1+r)^T[p]-1);
constraint2{p in P}:Capital_Cost[p]>=(R[p]*cp[p])/ (H*f[p]*1.1);
constraint3{p in P}:l[p]=R[p] *(1+e[p])/(r-0.01)*(1-((1+e[p])/(1+r))^T[p]);
constraint4{p in P}:lcoe[p]>=Capital_Cost[p]+l[p]*om[p]/ (H*f[p]*1.1) +
(l[p]*fuel[p])/(f[p]*1.1);

```

8.6 LCOE Calculator – Data

```
set P:= Wind3 Wind4 Wind5 Wind6 Solar Hydro_Bui Hydro_Ako_Kpong Hydro_mini T1 T2 T3
T4 T5 T6 T7 T8 T9 T10 T11 T12 T13 T14 T15 Nuclear ;
```

```
param r:=0.1675;
```

```
param H:=8760;
```

param:	cp	f	om	e	T	fuel	:=
Wind3	2330000	0.3	87600	0.01	25	0	
Wind4	2330000	0.325	87600	0.01	25	0	
Wind5	2330000	0.375	87600	0.01	25	0	
Wind6	2330000	0.4	87600	0.01	25	0	
Solar	2258000	0.18	22580	0.005	25	0	
Hydro_Bui	1975000	0.27	49350	0.005	80	0	
Hydro_Ako_Kpong	2140000	0.59	53528	0.005	46	0	
Hydro_mini	2120000	0.55	37000	0.005	40	0	
T1	1020000	0.75	30000	0.01	25	7.26	
T2	1020000	0.75	30000	0.01	25	14.52	
T3	1020000	0.75	30000	0.01	25	21.78	
T4	1020000	0.75	30000	0.01	25	29.04	
T5	1020000	0.75	30000	0.01	25	36.3	
T6	1020000	0.75	30000	0.01	25	43.56	
T7	1020000	0.75	30000	0.01	25	50.82	
T8	1020000	0.75	30000	0.01	25	58.08	
T9	1020000	0.75	30000	0.01	25	65.34	
T10	1020000	0.75	30000	0.01	25	72.6	
T11	1020000	0.75	30000	0.01	25	79.86	
T12	1020000	0.75	30000	0.01	25	87.12	
T13	1020000	0.75	30000	0.01	25	94.38	
T14	1020000	0.75	30000	0.01	25	101.64	
T15	1020000	0.75	30000	0.01	25	108.9	
Nuclear	1940000	0.9	650000	0.01	60	5.2;	

Where T_i is fuel at $\$/\text{MW}$. Thus T1 is fuel at $\$/\text{MW}$