OPTIMISING ENERGY SYSTEMS OF GHANA FOR LONG-TERM SCENARIOS

A thesis submitted for the degree of

Doctor of Philosophy

By

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DECLARATION

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. The work was carried out in accordance with the regulations of the Brunel University London and the material has not been submitted, in part or in whole, for any other degree at this or any other university.

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ABSTRACT

This study explored energy solutions for Ghana by analysing alternative pathways from 2010 to 2040. The Long-range Energy Alternating Pathways (LEAP) tool was used the scenarios analysis. Four scenarios were developed based on key influencing factors identified in the literature. These are Base case, Coal, Modest Renewable Energy Technology (RET), and High RET scenarios. The Base case scenario was based on government-planned expansion and assumed no shift in policy. The Coal scenario assumed the same expansion trend as Base case with introduction of coal plants replacing a percentage of natural gas generation. Modest and High RET scenarios examined the development of the system with increased renewable energy integration. The results revealed that overall benefits are achieved with higher integration of renewable energy technologies. Economic benefits of 0.5 – 13.23% is achieved in the RET scenarios depending on the cost development over the 30 year study period. The high RET offers the highest economic and environmental benefits. Subsequently, the optimal development of the system was examined using the LEAP/OSeMOSYS (Open Source Energy Modelling System) optimisation methodology. The least cost system developed by LEAP (Optimum scenario), was used as a reference to examine future possible energy policy direction in Ghana. The policy constraints analysed included emission targets, carbon taxes and transmission, distribution losses improvements and demand side efficiency. The results show that: suitable policies for clean power generation have an important role in CO_2 mitigation in Ghana. The introduction of carbon minimisation policies will also promote diversification of the generation mix with higher penetration of renewable energy technologies. The study proposes promoting energy efficiency and improvement in transmission and distribution losses and utilisation of renewable energy as the best energy strategy for Ghana. Ghana needs ambitious targets, policies and implementation strategies to enhance energy efficiency, and decrease demand in the long term. Stable funding and promotion of transparent policies are required to promote high development of renewable energy technologies.

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DEDICATION

I dedicate this Thesis to my wife (Victoria Wepea Weobong) and children (Wopolo Louis Awopone and Wemanga Marryann Awopone) for their love, prayers, support, sacrifice and patience during the period of my study.

The Thesis is also dedicated to my mother (Selorem Minyila), grandmother (Late Tipura Minyila) as well as my siblings for their prayers and support.

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ABBREVIATIONS

AIM	Asian-Pacific Integrated Model
AR4	Forth Assessment Report
ARDL	Autoregressive Distributed Lag Model
ARIMA	Autoregressive Integrated Moving Average
ASF	Atmospheric Stabilisation Framework
BESOM	Brookhaven Energy System Optimisation Mode
BET	Biomass Energy Technologies
BIGCC	Biomass Integrated Gasification Combined Cycle
BPA	Bui Power Authority
CDM	Clean Development Mechanism
CEL	Cenit Energy Limited
CFL	Compact Fluorescent Lamps
CIA	Cross Impact Analysis
COMPOSE	Compare Options for Sustainable Energy
COMPOSE	Compare Options for Sustainable Energy)
CT	Low Carbon Tax Scenario
CT1	Modest Carbon Tax Scenario
CT2	High Carbon Tax Scenario
DRI-Brookhaven	combination of Hudson-Jorgenson and BESOM models
EC	Energy Commission Ghana
ECG	Electricity Company of Ghana
ECMS	Energy Consumption Management System
EE	Low Energy Efficiency Scenario
EE1	Modest Energy Efficiency Scenario

EE2	High Energy Efficiency Scenario
EFOM	Energy Flow Optimisation Model
Env. Ext	Environmental Externalities
ESPM	Energy Supply Planning Model
ET	Emission Target
ET1	Modest Emission Target Scenario
ET2	High Emission Target Scenario
ETA-MACRO	Energy Technology Assessment and Macroeconomic Growth
ETSAP	Energy Technology Systems Analysis Programme
FIP	Feed-In Premiums
FIT	Feed-In Tariffs
GDP	Gross Domestic Product
GEDAP	Ghana Energy Development And Access Project
GHG	Greenhouse Gas
GLPK	GNU Linear Programming Kit
GRIDCO	Ghana Grid Company
GW	Gigawatt
GWh	Gigawatt hour
GWP	Global Warming Potential
HOMER	Hybrid Optimisation of Multiple Energy Resources
ICLEI	International Council for Local Environmental Initiatives
IEA	International Energy Agency
IFS	Interactive Future Simulations
IIASA	International Institute of Applied Science Analysis
INDC	Intended Nationally Determined Contribution

INFORSE	International Network for Sustainable Energy
INTERAX	Interactive Cross Impact Simulation
IPCC	Inter-governmental Panel on Climate Change
IPP	Independent Power Providers
kWh/m^2	kilowatt hour per metre square
LCO	Light Crude Oil
LEAP	Long-rang Energy Alternative planning
LPG	Liquefied Petroleum Gas
lpsolve	Linear Programming solver
m/s	metres per second
MARIA	Multiregional Approach for Resources and Industry Allocation Model
MARKAL	Market Allocation
MDG	Millennium Development Goals
MEPS	Minimum Energy Performance Standards
Mesap PlaNet	Modular Energy-System Analysis and Planning Environment Planning Network
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental impacts
MILP	Mixed Integer Linear Programming
MiniCAM	Mini Climate Assessment Model
MMbbl	Million barrels
MMBtu	Million British Thermal Units
MMtCO2e	Million Metric Tons Carbon Dioxide Equivalent
MSW	Municipal Solid Waste

MT	Metric Ton
MW	Megawatt
NASA	National Aeronautics and Space Administration
NEDCO	Northern Electricity Distribution Company
NEMS	National Energy Modelling System
NG	Natural Gas
NREL	National Renewable Energy Laboratory
NRET	Non-conventional Renewable Energy Technologies
O&M	Operational and Maintenance
Oil	Crude oil
OPT	Optimum scenario
OSeMOSYS	Open Source Energy Modelling System
PAM	Partial Adjustment Model
PIES	Project Independence Evaluation System
PMT	Probabilistic Modified Trends
POLES	Prospective Outlook on Long-Term Energy Systems.
Powerplan	Computer Model for Energy System Analysis
PURC	Public Utility Regulatory Commission
PV	Photovoltaic
RAND	Research and Development
RESGEN	Regional Energy Scenario Generator
RET	Renewable Energy Technologies
RETScreen	Renewable Energy Technology Screening Model
SDG	Sustainable Development Goals
SEP	Soft Energy Paths

SGM	Second Generation Model
SMEC	Snowy Mountains Engineering Corporation
SNEP	Strategic National Energy Plan
SOPCL	Saltpond Offshore Producing Company
SRI	Stanford Research Institute
SWERA	Solar and Wind Energy Resource Assessment
TAPCO	Takoradi Thermal Power Station
TCTPP	Tema Cenit Thermal Power Plant
TD	low Transmission and Distribution scenario
TD1	Modest Transmission and Distribution scenario
TD2	High Transmission and Distribution scenario
TED	Technology Database
TIA	Trend-Impact Analysis
TIMER	Targets-Image Energy Regional Model
TIMES	The Integrated MARKAL-EFOM System
TJ	Tera joules
TRACE	Tool for Rapid Assessment of City Energy
TWh	Terawatt hours
UNFCCC	United Nations Framework Convention on Climate Change
VALCO	Volta Aluminium Company
VRA	Volta River Authority
WASP	Wien Automatic System Planning Package
WEM	World Energy Model

CHAPTER 1

INTRODUCTION

This chapter presents the context, the focus and the structure of the study. It consists of the background and justification of the research, which describes the existing problems and the need for the research. The chapter also describes the research framework used, and presents the objectives, structure and significance of the study.

1.1 Background and Justification

Ghana faces serious energy related challenges as the country struggles to meet generation requirement. The electricity supply system of the country is characterised by power outages, which have serious implications on the quality of life as well as industrial development. Reliable and affordable electricity generation is an indispensable commodity in the technological development of any country [1, 2].

Even though the country is unable to meet the current demand [3], the expanding economy, coupled with increasing population and urbanisation will lead to much more energy demand in the future. Official demand projections [4, 5] as well as those by Abledu [6] and Adom & Bekoe [7] projected aggregated demand of Ghana to increase at 7 – 12% annually in the next 2 decades, depending on the Gross Domestic Product (GDP) and population growth rates. This does make the development of a realistic generation expansion plan essential if the country is to achieve its long-term development goals. Inadequate appropriate expansion has resulted in the current situation where the generation capacities can only meet about 65% of the current demand as at March 2014 [3].

The conventional grid generation in Ghana is by Hydro, with the Akosombo Hydro dam providing almost all the grid power when it was commissioned in 1966 [8]. The high dependence on hydropower makes the country's generation to be influenced by seasonal cycles, which include dry and raining seasons. Occasional cases of prolonged dry seasons coupled with insufficient rainfall during the rainy seasons have resulted in blackouts and power rationing[1] as experienced in 1984 due to the severe drought conditions of 1983 [9]. Thermal power generation was introduced in 1987 to supplement the conventional hydroelectricity after the drought in 1983 underscored the need to diversify the country's generation system.

There is a growing interest in power generation systems worldwide because of the growing demand of power and the environmental implications of these power systems. The adverse environmental and societal impacts and fluctuation in the prices of fossil fuels in the world market has necessitated the exploitation of sustainable power generation technologies [10]. Goal 7 of the United National's Sustainable Development Goals (SDG), which replaces the previous Millennium Development Goals (MDG), stipulated that adopting technology that will ensure provision of clean energy in developing countries will not only encourage growth but will also help the environment [11]

The adverse environmental and societal impacts and fluctuation in the prices of fossil fuels in the world market has further necessitated the exploitation of sustainable power generation technologies. These technologies include renewable energy sources such as hydroelectricity, solar energy, wind, wave energy, bioenergy

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[1] Popularly referred to as "dumsor" in Ghana

and geothermal energy. Renewable energy sources are naturally replenished at rates that far exceed their consumption. They are also noted to have manageable environmental effects. Conventional renewable energy systems such as hydro generation have been part of generation systems worldwide. Wind and solar technologies have experienced significant growth in recent years. Global wind installed capacity at the end of 2015 was 432.88 Gigawatt (GW), representing a cumulative growth rate of 17% [12]. Twenty-six (26) countries have more than 1000 MW installed capacity. Seventeen of these countries are in Europe, with South Africa being the only African country. China, the world leader in wind generation has installed wind capacity of 145.36 Megawatt (MW) at the end of 2015 [12]. Other sources such as generation using ocean waves have received significant consideration in recent years.

Ghana is endowed with several renewable energy resources, which can be exploited to help meet the energy needs of the country. There is excellent solar radiation all year round, and in every part of the country, with an average radiation of 5.5 kilowatt hour per metre square (kWh/m^2). Sites suitable for medium and small hydro power plants have also been identified in various parts of the country with a potential of adding over 900 MW to the national grid if fully exploited. Sites near the coastal parts of the country have also been identified with excellent conditions for wind generation [13]

The sustainable energy decision-making is often unique and depends on the circumstances of each planning area. However, the growing global concern on the depletion of fossil fuels as well as the effect of generating plants on the environment makes energy planning decisions complex. The main challenge with the implementation of renewable energy system especially in developing countries such as Ghana has been their high capital investment. However, advancing scientific knowledge will lead to performance improvement and cost reductions of these technologies in the future. For instance, the cost of Photovoltaic (PV) cells has dropped from $76 /watt in 1977 to $0.50 /Watt in 2015. Investment decisions and policies to promote renewable energy system will significantly affect the level of greenhouse gases (GHG) in the future. Also, good decisions concerning the best choice of technologies for future years will avoid expensive changes in later years. This therefore provides a need for energy planning to develop the best generation mix making use of the available technologies, policies drivers as well as challenges.

The government of Ghana recognising the role of energy planning established the Energy Commission Ghana (EC) to manage and regulate the utilisation of the country's energy resources. The commission, which is the main agency for strategic energy planning, developed future demand and generation expansion plans of the country from 2006 to 2020. The results of this study, which were presented in the strategic energy plan of Ghana [4], is currently the benchmark for generation expansion in the country.

The EC's study examines three pathways for power generation in Ghana from 2006 to 2020. These options include Option1, which is an expansion plan based on thermal and 10% Non-conventional Renewable Energy Technologies[2] (NRET) by 2020, Option 2 based on thermal, Bui hydro plant and 10% NRET and Option 3, which is based on thermal, nuclear and 10% NRET. The current generation expansion plan of the country is based on option two. However, the NRET

[2] New renewable energy technologies does not include conventional large hydro generation plants.

dependable capacity as at March 2015 was only 0.03% [3] compared to the targeted 10%.

Apart from the EC's study, there is a general lack of research on the future development of the generation system of Ghana. Moreover, the EC's study only projected the energy system up to year 2020 based on year 2000 parameters, which does not fully represent the current situation. The study did not also fully assess the environmental impact of the future generation pathways and hence, did not consider the impact of introducing carbon minimisation policies such as carbon tax and emission targets on the future development of the generation system. Also, provisions were not made to identify the optimum cost model for generation expansion in Ghana. This is particularly important when investment decisions are to be made on NRET systems.

This thesis focuses on renewable energy technologies as a means for meeting the current and future electricity generation needs of Ghana. Renewable technologies are increasingly becoming attractive to many energy planners. However, their exploitation and acceptance especially in developing countries such as Ghana can only be realised if they can be seen to be competitive to conventional generation systems.

1.2 Objectives of the Study

The aim of this study is to provide accurate information on the economic and environment performance of renewable energy generation in the Ghanaian context and to outline strategies that could result in their increased deployment. The specific objectives are to:

1. assess energy resources, energy development and associated policies in Ghana
2. develop a model of the energy system for Ghana and explore future pathways by considering key drivers of energy policy
3. analyse the growth of Ghana power sector by examining the technical, economic and environmental performance under various scenarios
4. develop and analyse least cost generation options based on cost-benefit analysis including the introduction of carbon taxes and emission reduction targets
5. recommend energy policy options that can improve the long term electrical generation in Ghana.

1.3 Significance of the Study

The study provides an improved framework for detailed examination of both demand and supply sectors of energy systems. The improved framework is a hybrid system, which was built on Schwartz methodology to include quantitative analysis. This enables detailed energy, economic and environmental analysis of generation system.

The developed Ghana LEAP (Long-rang Energy Alternative Planning) presents an up to date energy model of the generation system of the country. This is the first of its kind with demand sector making use of the bottom-up approach, which covers energy intensive sectors. This will add to the general body of knowledge in the Ghanaian context.

The generation pathways derived provide additional information on the possible future development of the generation system of Ghana. This provides a comprehensive library to guide policy makers to formulate strategies and policies to shape the generation system.

Furthermore, the study developed an optimum model for generating power in Ghana based on the available resources and technologies under different policy directions. This provides empirical analyses to establish the most effective policy direction that might promote high renewable integration into the generation mix of Ghana.

Finally, findings of this study may be applicable to other countries especially developing countries where hydro and thermal generation dominates the generation system. This will be useful for other sub-Saharan African countries. These findings will be useful for all players in the energy sector. The analysis of the relationship between energy, economy and environment, will enable technocrats and policy makers to make informed decisions and provide advanced knowledge to guide energy policy researchers to shape future energy policies.

1.4 Research Framework

The research focuses on modelling and analysing the future generation system of Ghana. The research framework applied several methodologies including theoretical framework, empirical analysis and conclusion. Figure 1-1 shows the schematic diagram of the methodology framework and structure of the thesis.

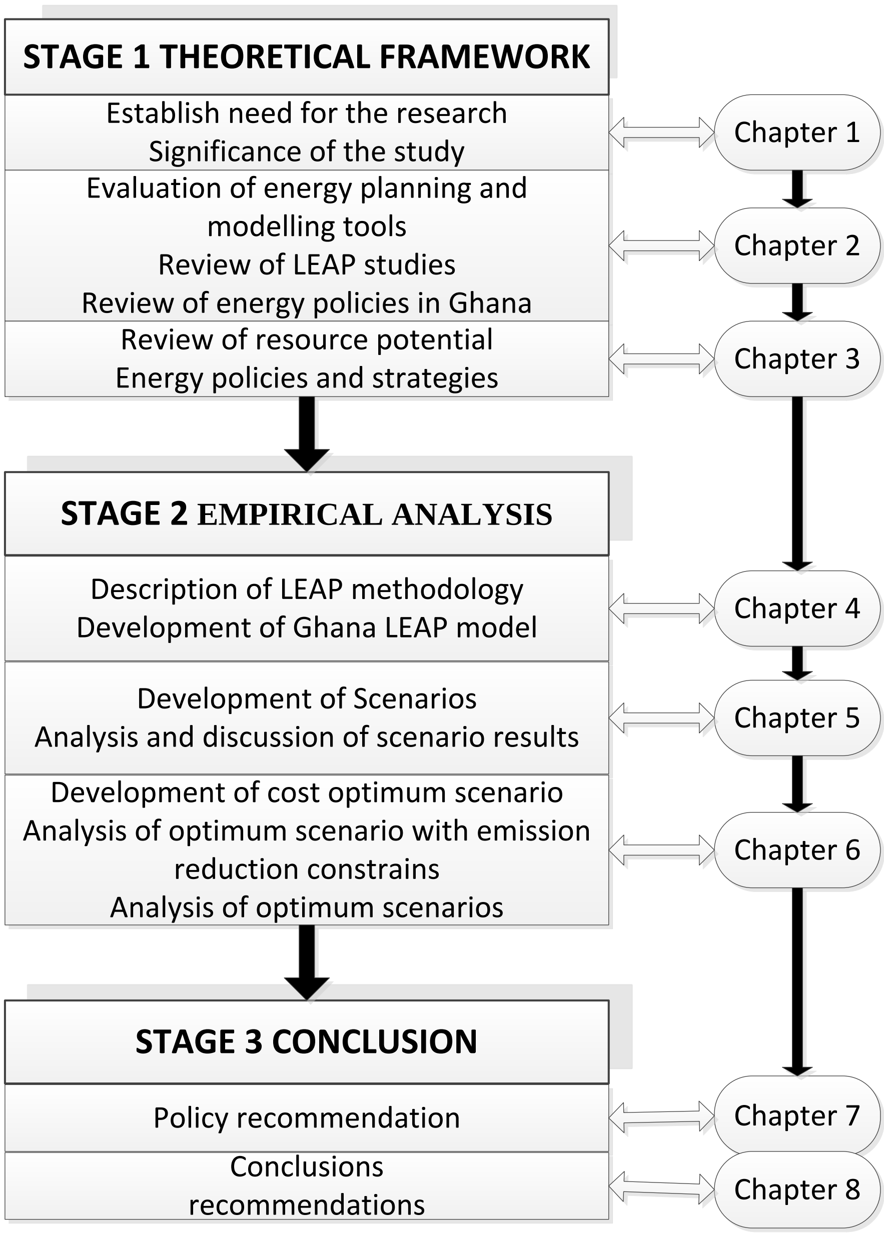


Figure 1-1 Thesis framework and structure

The theoretical framework established the need for the study by providing an overview of the generation system of Ghana – past and present, and the various agencies involved in the country's power sector. It includes a comprehensive review of available resources, trend in demand, supply and operational structure of the generation system. This stage also reviewed energy planning tools identified using LEAP methodology.as the preferred tool for the study.

The empirical analysis stage involves the development of the Ghana LEAP model and scenarios. The scenarios were developed by considering key factors relating to energy access and development in Ghana. This stage also describes alternative cost optimum scenarios under different constraints. This section provides the benchmark for comparison with similar studies and establishes the core significance of the study.

The final section evaluates sustainable strategies for long-term generation development in Ghana. The sections also provides a summary of main findings and discusses potential for high renewable energy generation and carbon emission potential of the country up to 2040.

1.5 Structure of the Thesis

The study is organised into seven chapters. Chapter 1 provides the background, which identifies the need for the research, and describes the objectives and significance of the thesis. The chapter also outlines the research framework and structure.

Chapter 2 presents overview of the current situation of the generation system of Ghana. The chapter provides an extensive review of the energy resources as well as the various energy policies and strategies implemented in the country.

In Chapter 3, a review of literature related to the topic was discussed. An empirical review of energy planning tools, studies applying LEAP and renewable energy policies were discussed. This chapter enables assessment of research frameworks applied in similar studies and identifies key features and input data for the research.

The method employed in conducting the research is described in Chapter 4. The chapter provides description of the LEAP model as well as development of the Ghana LEAP model.

Chapter 5 developed and analysed three scenarios and compared the development of the system under different renewable energy penetrations.

Chapter 6 presents a description of the development of cost optimum scenarios for the generation system. The chapter also analyses the development of the optimum system under various carbon minimisation constraints.

Chapter 7 presents analysis of renewable energy and energy efficiency policies and recommendation for their increased deployment.

Finally, Chapter 8 presents the findings and conclusion, as well as suggestions for future research.

1.6 Publications

1. Awopone, A.K., Zobaa, A.F. and Banuenumah, W., 2017. Techno-economic and environmental analysis of power generation expansion plan of Ghana. *Energy Policy*, *104*, pp.13-22. http://dx.doi.org/10.1016/j.enpol.2017.01.034

2. Awopone, A.K. and Zobaa, A.F., 2017. Analyses of optimum generation scenarios for sustainable power generation in Ghana. *AIMS Energy, 5 (2), pp 193 – 208. DOI: 10.3934/energy.2017.2.193*

3. Awopone, A.K., Zobaa, A.F. and Banuenumah, W., 2017. Assessment of Optimal pathways for power generation system in Ghana. *Cogent Engineering*, 4: 1314065. http://dx.doi.org/10.1080/23311916.2017.1314065

CHAPTER 2

OVERVIEW OF POWER SECTOR OF GHANA

The limited reserves of fossil fuels and global environmental concerns over their use for electric power generation have increased the interest in the utilization of renewable energy resources. Rapid advances in photovoltaic technologies have brought opportunities for the utilization of solar resources for electric power generation worldwide. However, this method of generating power, and other Renewable Energy Technologies (RET) have not been fully exploited. The chapter presents an overview of the generation system of Ghana. It provides a comprehensive review of the energy resources in the country. The chapter also provides an insight into the organisational structure of the power sector of Ghana and the energy strategies developed over the years to promote the development of RET.

2.1 HISTORY OF POWER GENERATION IN GHANA

The conventional grid generation in Ghana is by Hydro, with the Akosombo Hydro dam providing almost all the country's electricity power when it was commissioned in 1966. The Akosombo generating plant was originally constructed with a total installed capacity of 588 MW. The capacity was increased to 912 MW in 1972 with an addition of two generating units to the original four. Prior to the construction of the dam, power supply in Ghana was through isolated diesel generating plants, which were located near key load centres. Ghana Railway Corporation constructed the first of these generators in Sekondi in 1914 [8].

The construction of the Akosombo hydro plant was tied to the Volta Aluminium Company (VALCO). The idea was to develop the huge bauxite reserves in the country to make use of the energy from the Akosombo dam. This was conceived by the then Director of Geological Survey, Sir Albert Ernest Kitson [8]. However, the plan was not implemented until Ghana became a republic in 1960 and the country's first leader brought the vision to reality. The establishment of VALCO was because of the vision of the first President of the Republic of Ghana, Dr Kwame Nkrumah, to establish an integrated aluminium industry in the country. The Company is therefore a product of the meeting of minds of Dr Nkrumah and Edgar Kaiser, Chairman and Founder of Kaiser Aluminium & Chemical Corporation, the immediate past majority shareholder of VALCO [14]. Total domestic load at the time of the construction of the Akosombo Dam (excluding VALCO) was approximately 540 gigawatt hour (GWh) with a corresponding peak demand of about 100 MW [8]. This made the construction of such a big generating plant appear not to make economic sense at the time. The meeting between Dr Nkrumah and Edgar Kaiser resulted in the signing of a purchase agreement between the government of Ghana and VALCO, with VALCO providing the financial guarantee needed for the construction of the dam. Under the agreement, VALCO was to purchase not less than 300 MW for a period of 30 years with a right to extend for a further 20 years and was required to pay for the power even if not used [14]. The smelter was subsequently constructed consisting of five portliness capable of producing 200 000 metric ton (MT) of primary aluminium annually [14]. The company today, which is now 100% own by the Government of Ghana, operates about 20% of its rated capacity because of insufficient supply of power. An additional hydro dam, Kpong dam, was constructed near Akuse, 24 kilometres (km) down stream of Akosombo dam. The

Kpong hydroelectric plant was commissioned in 1982 with an installed capacity of 160 MW.

Thermal power generation was introduced to supplement the conventional Hydroelectricity after the drought in 1983 underscored the need to diversify the country's generation system. The introduction of Thermal power generation into the generation mix of the country occurred in 1997 with the construction of a combined cycle power plant with an installed capacity of 330 MW at Aboadze near Sekondi-Takoradi. The Takoradi Thermal Power Station (TAPCO), as it is officially called, was eventually expanded to 550 MW with the addition of two 110 MW combustion turbine plants in year 2000. This marked the beginning of a gradual shift to thermal generation in the country.

The near exhaustion of the country's hydroelectric resources has resulted in gradual expansion in thermal generation. Figure 2-1 shows the percentage shares in generation by fuel type from year 2000 to 2014.

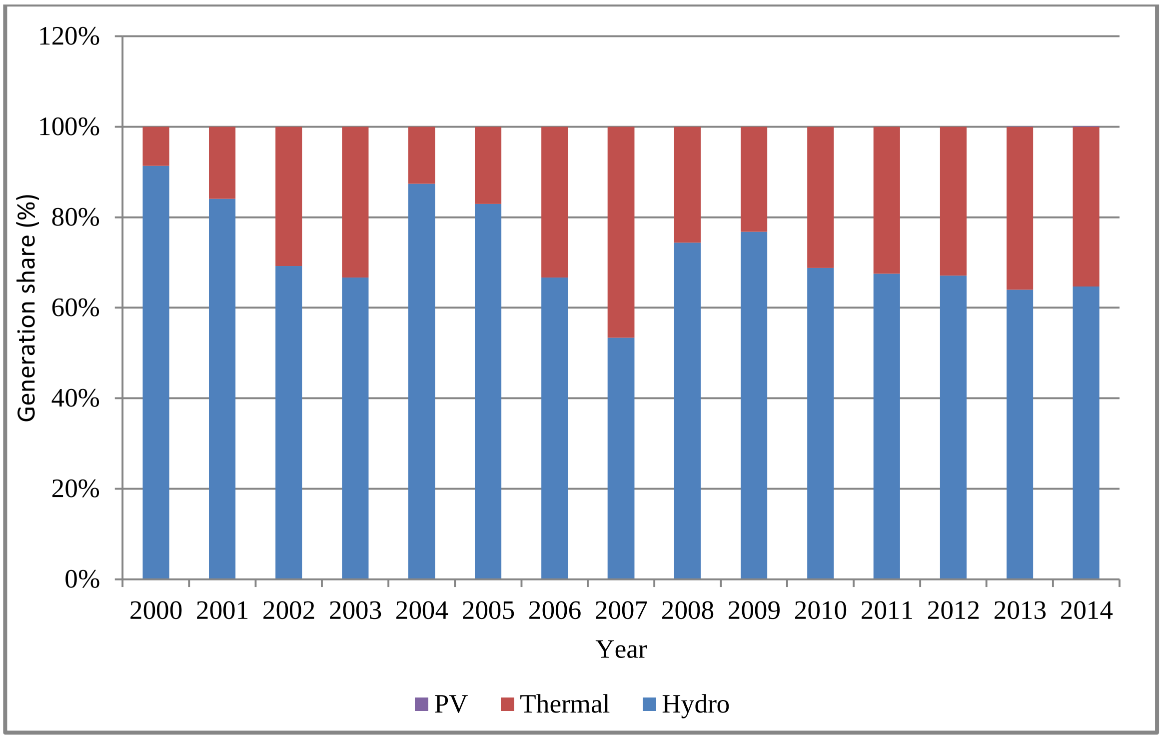


Figure 2-1 Trend in energy generation from 2000 to 2014 [3, 15]

It is observed from Figure 2-1 that hydropower which contributed about 92 % of the installed capacity in 2000, now contribute 65 % as at December 2014. This trend is most likely to continue if there is no change in policy. The current generation expansion plan is dominated by proposals to construct new thermal plants including coal plants.

2.2 THE EXISTING GENERATION SYSTEM

Grid power production in Ghana is mainly from hydro and thermal sources. The installed capacity as at March 2014 was 2851 MW with a firm generation of 2587 MW [3]. The installed capacity was made up of 1580 MW (55.4%) from the three hydro dams, 1248 MW (43.8%) from Thermal plants and only 2.5 MW (0.09%) from photovoltaic plant. All the plants are operated by Volta River Authority (VRA) except Bui, which is operated by Bui Power Authority (BPA). VRA and BPA are both government agencies. Sunon-Asogli, and Cenit Energy Limited (CEL) are private entities which contribute about 11.6% of the installed capacity [3]. Table 2-1 shows the Power generation capacity of Ghana as at March 2014.

Table 2-1 Generation capacity of Ghana as at March 2014 [3]

Plant	Fuel	Owner	Capacity (MW)				Generation	
			Install	%	Dependable	Available	GWh	%
Akosombo hydro	Hydro	VRA	1020		900	743	6509	
Kpong hydro	Hydro	VRA	160		140	84	730	
Bui hydro	Hydro	BPA	400		380	130	1148	
Total hydro			**1580**	**55.4**	**1420**	**956**	**8387**	**64.7**
TAPCO	Oil/NG	VRA	330		300	102	890	
TICO	Oil/NG	VRA	220		200	82	712	
Takoradi T3	NG	VRA	132		125	144	1255	
Tema thermal 1	Oil/NG	VRA	110		100	80	697	
Tema thermal 2	NG	VRA	50		45	26	223	
Sunon-Asogli	NG	IPP	200		180	58	513	
Mines reserve	Oil/NG	VRA	80		70	10	87	
CEL	Oil/NG	IPP	126		70	22	195	
Total Thermal			**1248**	**43.8**	**1130**	**524**	**4574**	**35.3**
Navrongo Solar	Solar	VRA	2.5	0.001	2	2	4	
Total			**2851**		**2552**	**1482**	**12965**	

The main fuel for the thermal power plants in Ghana is light crude oil, diesel and natural gas. Even though most of the thermal plants were designed to operate on more than one type of fuel, natural gas is the preferred fuel when available because of its comparatively low cost. The main challenge with the running of the thermal plants is securing adequate supply of gas [3]. Plants that operate solely on natural gas contribute 26% of thermal generation. These plants are normally the worst affected when there is shortfall in the supply of gas.

2.3 DEMAND OUTLOOK

The actual power generated available to the national grid in 2014 was 11.4 TWh at a peak of 2000 MW [3, 5]. However, the total electricity requirement was estimated to be between 20.2 – 26.3 TWh if VALCO is allowed to work at full capacity, with a corresponding maximum demand of 2556 – 3100 MW [3, 5]. VALCO is the country's single non-utility consumer when operating at full capacity. The company consist of five smelters with a maximum demand of 320 MW with an annual consumption of about 2900 GWh of energy. This means that the current generation sources generate only about 65% of the current demand. This is compounded by the fact that, the demand is estimated to be increasing at a rate of 10% per anum because of increasing population and industrialisation [6].

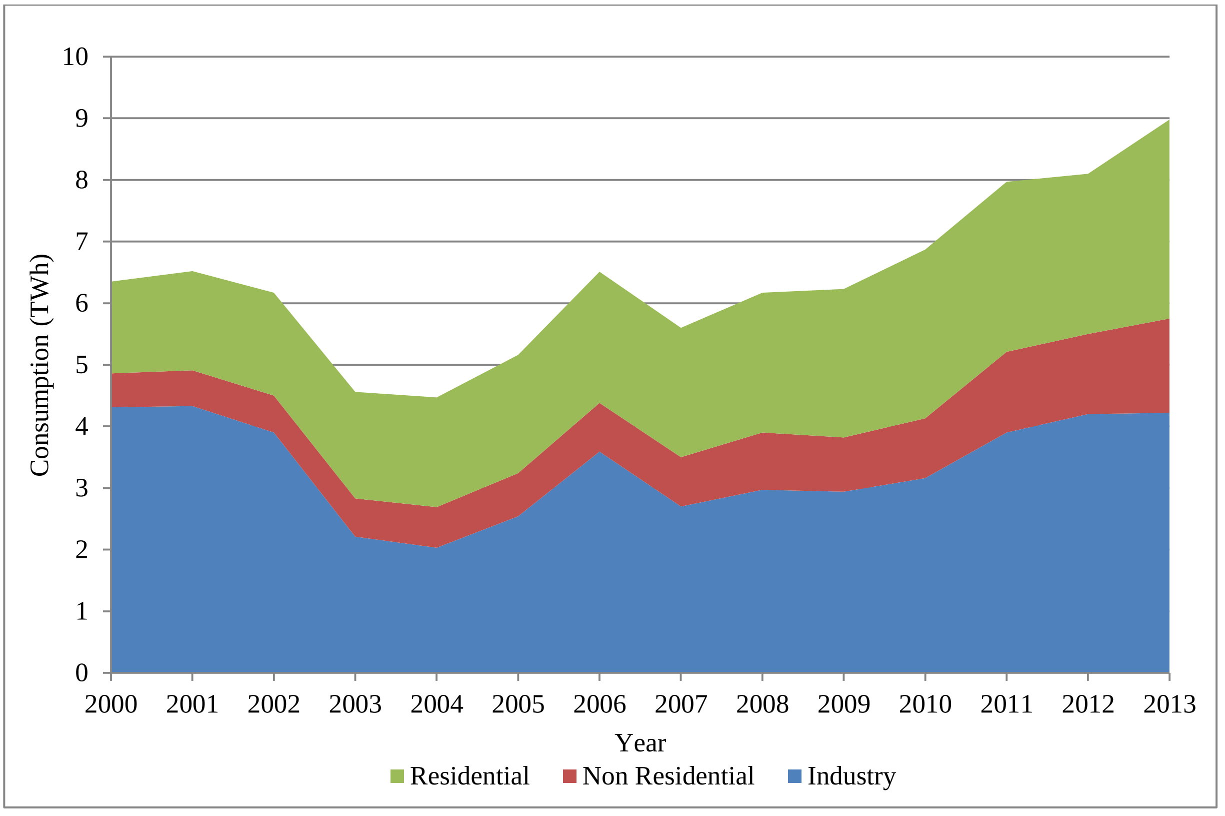


Figure 2-2 Share of grid power consumption by sectors [15, 16]

The main power consumers in Ghana can be classified under residential, non-residential (comprising the commercial and service sectors) and industry. The total generation consumed by class from 2000 to 2013 is illustrated in Figure 2-2. The increasing population and expanding economy has resulted in a high demand for power over the years. However, it is apparent from the figure that the generation system is not expanding with demand. The generation in 2003 was about 28% less than that of the generation in 2000. This was due to insufficient rainfall in 2003, which affected the operation of hydropower systems. The generation system was unable to reach the 2000 value until 2009, thereafter, increasing marginally to 9.36 TWh in 2013, representing a growth rate of 3.6%, which is less than half the projected demand growth rate.

The industrial sector of the country is the worst affected in favour of domestic consumers whenever there is inadequate supply. A detailed representation of share of energy available to industry from 2000 to 2013 is presented in Table 2-2.

Table 2-2 Grid electricity supply to industrial sector [15]

	Energy supplied (TWh)													
	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
VALCO	2.50	2.56	2.06	0.25	0.01	0.26	1.20	0.21	0.17	0.01	0.01	0.60	0.60	0.59
Mines	0.63	0.57	0.56	0.57	0.60	0.75	0.87	1.0	1.14	1.25	1.24	1.30	1.40	1.46
Others	1.17	1.20	1.28	1.38	1.42	1.53	1.52	1.48	1.65	1.66	1.91	2.00	2.22	2.18
Total	4.30	4.33	3.90	2.20	2.03	2.54	2.59	2.69	2.96	2.92	3.16	3.90	4.22	4.20
	Sectorial energy as percent of share of industry													
VALCO	58.14	59.12	52.82	11.36	0.49	10.24	33.43	7.81	5.74	0.34	0.32	15.38	14.22	13.33
Mines	14.65	13.16	14.36	25.91	29.56	29.53	24.23	37.17	38.51	42.81	39.81	33.33	33.18	34.76
Others	27.21	27.71	32.82	62.72	69.95	60.24	42.34	55.02	55.74	56.85	60.44	51.28	52.61	51.90
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Sectorial energy as percent of total electricity													
VALCO	39.26	39	33.44	5.43	0.22	4.94	18.27	3.74	2.69	0.16	0.14	7.52	7.02	5.99
Mines	9.89	8.68	9.09	12.38	13.27	14.26	13.25	17.79	18	19.51	17.4	16.29	16.37	15.61
Others	18.38	18.28	20.78	29.97	31.4	29.09	23.14	26.33	26.07	25.91	26.81	25.08	25.96	23.3
Total	67.54	65.97	63.31	47.78	44.88	48.3	54.66	47.86	46.76	45.57	44.35	48.9	49.35	44.9
	Index 2000 = 1.00													
VALCO	1.00	1.02	0.82	0.10	0.00	0.10	0.48	0.08	0.07	0.00	0.00	0.24	0.24	0.22
Mines	1.00	0.90	0.89	0.90	0.95	1.19	1.38	1.59	1.81	1.97	1.97	2.06	2.22	2.32
Others	1.00	1.03	1.09	1.18	1.21	1.31	1.30	1.26	1.41	1.42	1.63	1.71	1.90	1.86
Total	1.00	1.01	0.91	0.51	0.47	0.59	0.83	0.62	0.69	0.68	0.73	0.91	0.98	0.98

The total energy supplied to industry also reduced from 4.3 TWh in 2000 to 4.2 TWh in 2013, whilst that of residential saw an increase from 1490 GWh to 3600 GWh within the same period. This represents a reduction of energy to industry from about 68 – 45% in 2000 and 2013 respectively. The shift in energy consumption from industry to household has negative impacts on manufacturing, employment and overall economic development.

The prevailing inadequate energy supply is thus greatly affecting the industrial development of the country. The energy situation to industry is even more worrying because VALCO, which used to consume 2.5 TWh in 2000 representing about 58% of the energy supplied to industry and 39.4% of the total power generated, received only 0.59 TWh in 2013. The company was compelled to curtail operation during the energy crises in 2013 and has since not been able to operate beyond two units due to inadequate power supply [15]. The gold mining industry has since overtaken VALCO as it received 34.5% of the share of energy to industry in 2013. It is interesting to note that the total amount of energy supplied to the industrial sector since 2001 has been below the 2001 value (Table 2-2).

One of the primary developmental indicators of any society in the world today is the availability of modern and reliable energy supply. There is a direct link between access to cleaner and affordable energy, and poverty. This is demonstrated by the fact that the poor mostly in rural Ghana, constitute the majority of the people who rely mainly on biomass for cooking and lighting [17]. In general, reliable power supply helps promote sustainable human development and is an essential input for achieving most of the MDGs. It should be emphasised that even though almost every aspect of society today depends on the availability of electricity to operate, the provision of electricity to rural households alone cannot eliminate poverty. Poverty reduction depends greatly on the ability to consume the services and products resulting from availability of electricity. The country therefore needs to, as a matter of urgency, explore all available energy resources to expand its power generation capacity if it is to benefit from the growing industrialisation, provision of essential services, as well as meeting the demand of the growing domestic consumers.

2.4 ENERGY RESOURCES IN GHANA

2.4.1 Fossil Fuel Resources

The exploration for crude oil in Ghana can be traced back to the latter part of the 19^{th} century with the construction of onshore wells near La Cote d'Ivoire border. In 1965, the Ghana geological survey department with technical assistance from the Romanian government undertook exploration drilling at Anloga and Atiavi, towns located at the southwestern coast of the country [18].

In 1970, the Saltpond field was discovered by Signal-Amoco consortium with an initial appraisal potential of 3600 barrels per day. However, the consortium relinquished the concession at the end of 1979. The Saltpond Offshore Producing Company (SOPCL) currently manages the oil field. Phillips, Zapata, Oxoco, Agip consortium of companies, discovered natural gas in Cape Three Points in 1974. There was however, no public appraisal of the reserves in this discovery [18].

Despite all these earlier findings, the production of oil and gas in commercial quantities started in 2010 after the discovery of the Jubilee Field in 2007 by Tullow oil and Kosmos Energy. The reserves of the Jubilee field with estimated to be up to 3 billion barrels of sweet crude oil [19]. The initial production of 80,000 barrels per day increased to between 110,000 to 115,000 barrels per day by the first quarter of 2013 and an estimated projection of natural gas of about 140 million cubic feet per day [15]. Figure 2-3 shows the location of the most notable oil fields in Ghana. The exact location of some of these fields is currently under dispute between the governments of Ghana and La Cote d'Ivoire.

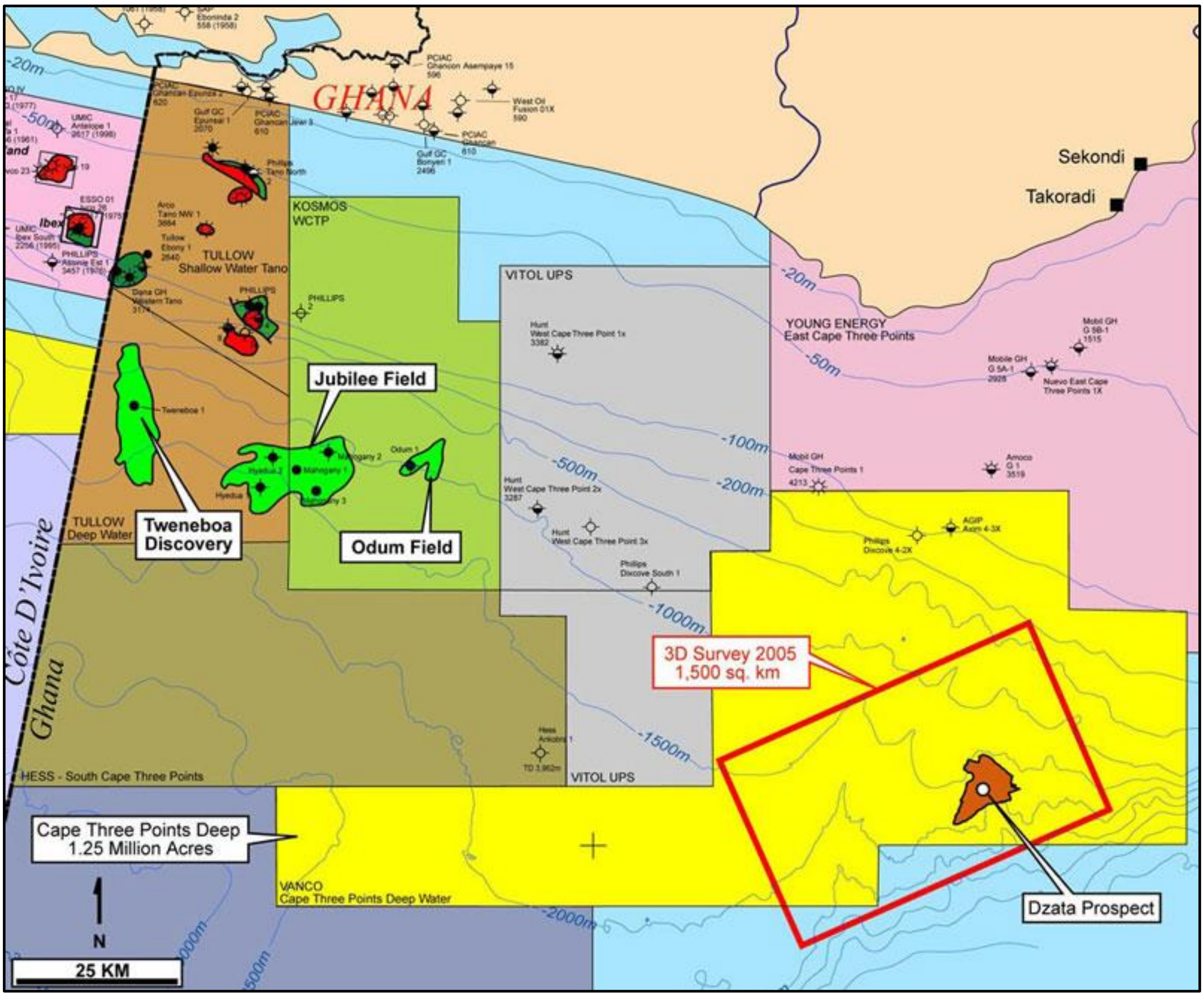


Figure 2-3 Ghana's oil findings [19]

Ghana is ranked 45th and 74th in the world for proven crude oil and natural gas reserves respectively. The Central Intelligence Agency country fact file estimates the proven crude oil reserves of 660 million barrels (MMbbl) as at January 2015 and 22.65 billion m^3 of Natural gas as at January 2014 [20] Ghana is however not yet credited with any coal deposit for commercial production.

2.4.2 Renewable Energy in Ghana

2.4.2.1 Solar resource

Ghana lies between latitudes $4°44'N$ and $11°11'N$. The western and eastern extremities lie at longitudes $3°15'W$ and $1°12'E$. The country has a tropical, hot and humid climate and a land area of approximately $238\,539\ km^2$. There is an abundant solar resource throughout the year in all parts of the country. This resource however varies slightly across the country with the highest occurring in the northern savannah region. The long-term average solar energy incident on a horizontal surface of three selected sites from the northern, middle and southern parts of the country, which is Navrongo, Kumasi and Takoradi respectively, is illustrated in Figure 2-4.

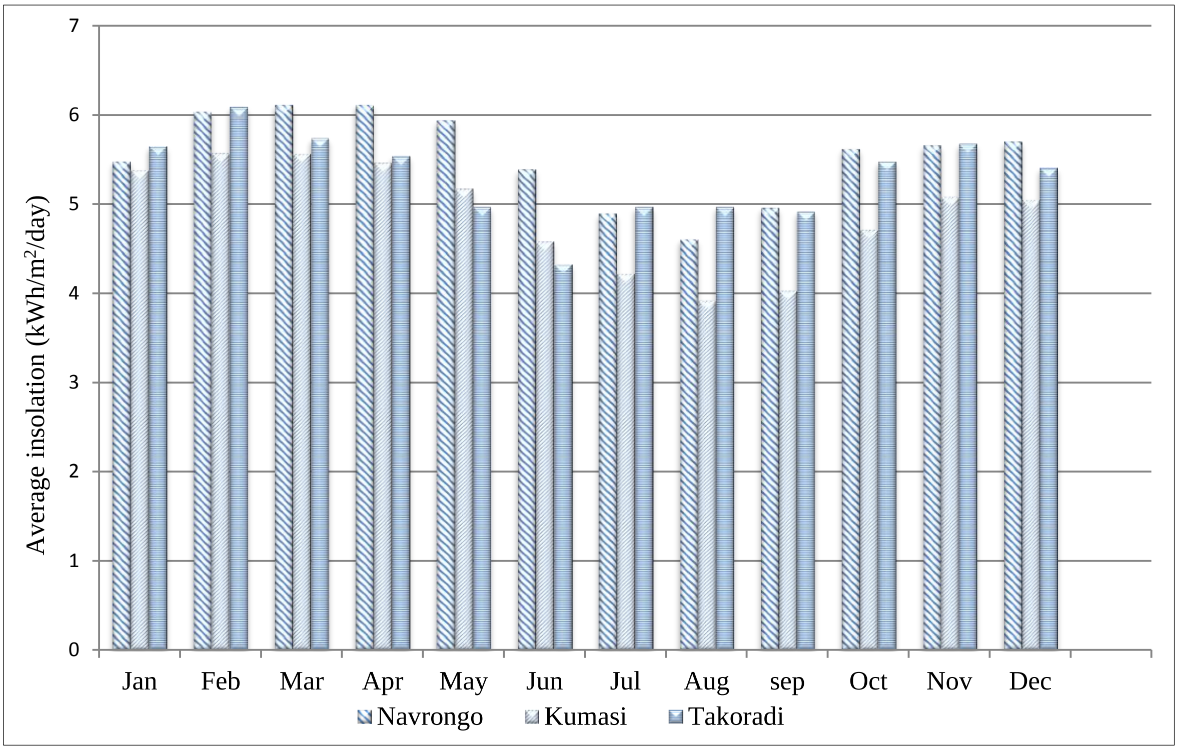


Figure 2-4 Solar Insolation of selected sites in Ghana in kWh/m^2/day [27, 28]

The direct conversion of the sun's energy into electricity is now considered as the most-promising renewable power source worldwide [21]. It is estimated that the available solar isolation in the world could generate1700 TW of electric power, 1% of which could meet the earth's present electric power demand [22]. Ghana has an excellent solar irradiation all year round with an average ground measurement of $3.92 \text{ to } 6.11\, \mathrm{kWh/m^2/day}$ [23] At this radiation level, the total energy potential is enormous, about 100 times the present energy consumption, even with a 10% recovery factor.

2.4.2.2 Hydropower potential

Hydropower is the second largest source of electricity worldwide after fossil fuels, contributing about 17% of the electricity consumed in the world [24]. Almost all the grid electricity produced in Ghana was from the Akosombo and Kpong hydropower stations until early 1998 when thermal generation was introduced into the national energy mix.

Figure 2-5 Hydroelectric potential of Ghana [25]

The country is endowed with many sites deemed suitable for the construction of large and medium hydro power plants with an additional combined potential of over 900 MW of power [25]. The potential sites for the construction of new hydroelectric plants, as well as the existing hydroelectric plants as illustrated in Figure 2-5. In addition to the these sites, over seventy small hydro sites have also been identified with a combined estimated potential of about 4 to 14 MW when connected to the grid [23].

2.4.2.3 Wind energy

Wind energy is one of the fastest growing renewable energy resources worldwide today [21] However, Ghana has not yet been able to harness this important renewable resource for grid power generation even though the country is endowed with sufficiently rich potential. The average wind speed measured about 10 km in the direction of the wind from the coastline of Ghana is about 5.5 metres per second (m/s) at a height 50 m from [26]. This makes the region suitable for wind energy systems especially with the developments in low speed wind turbines. Wind resource data obtained from NASA (National Aeronautics and Space Administration) surface meteorology data [27] for the three selected sites is presented in Figure 2-6

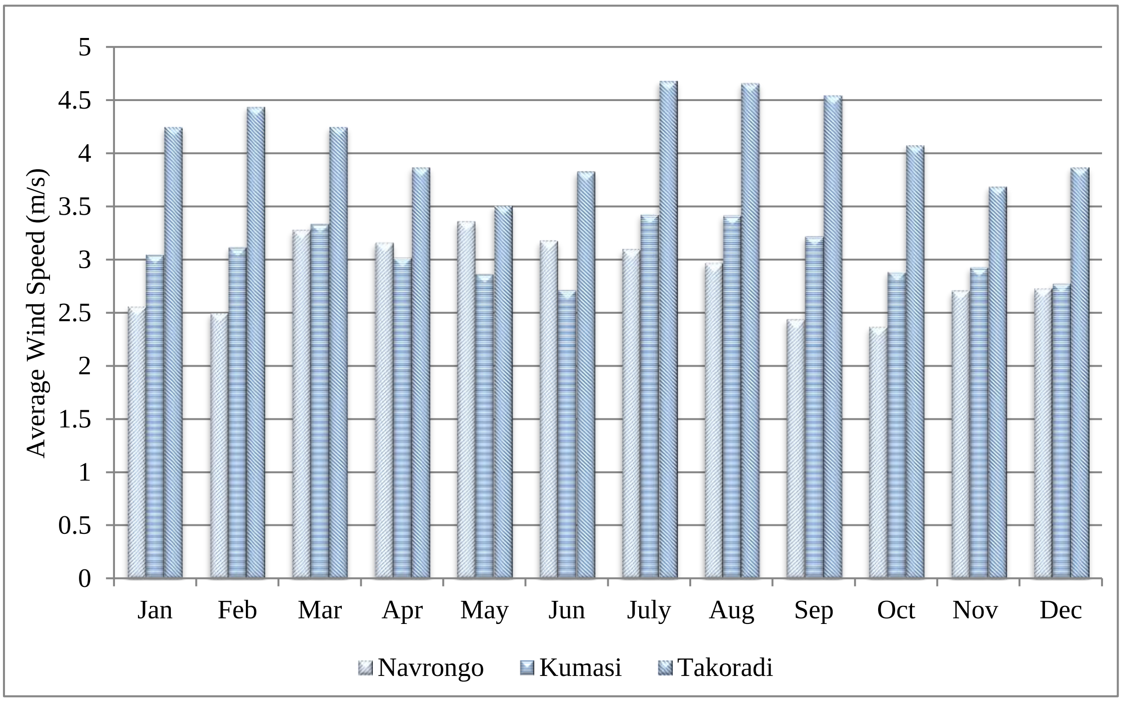


Figure 2-6 Wind Speed data for Selected Sites [27]

This wind resource data compare favorably with data compiled in the Solar and Wind Energy Resource Assessment (SWERA) report [28]. A wind resource map of Ghana developed by National Renewable Energy Laboratory (NREL) further shows the enormous potential of wind resource in the country (Figure 2-7).

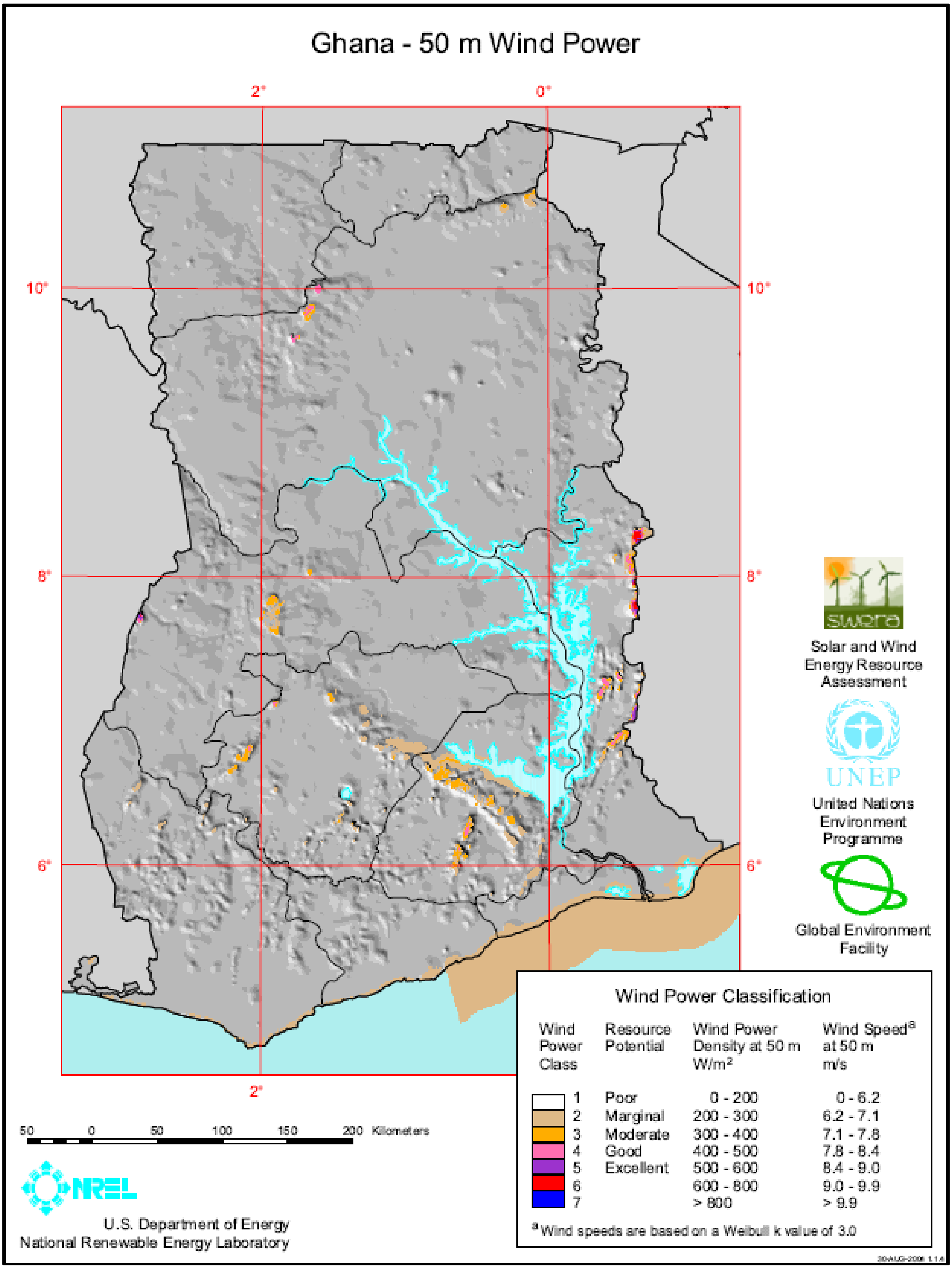


Figure 2-7 Wind resource map of Ghana [154]

It is observed from Figure 2-7 that very good wind conditions of 7.8 – 9.9 m/s occur along the country's eastern border with Togo. This has the potential to produce a wind power density of 600 – 800 W/m^2 in an area of about 300 - 400 km^2 [29].

A major reason for reluctance of utility power providers to explore renewable energy resources in developing countries such as Ghana has always been the cost factor. Comparatively however, wind power projects are less capital intensive [30] and their cost of energy is relatively cheaper than most renewables [29].

2.4.2.4 Biomass

Biomass is term used to describe organic matter that can be converted to fuel. This resource therefore includes wood and wood waste such as agricultural crops and residue, logging, wood processing waste, and animal waste such as livestock waste and poultry waste. In developing countries, biomass is extensively used as an alternative source of energy for cooking and other household activities [21]. Charcoal and firewood from biomass, are the main fuels for cooking in Ghana especially in the rural areas. However, the viability of generating power from biomass has not been fully explored in Ghana.

Globally, biomass is increasingly becoming a clean alternative source of energy to fossil fuels because of the greenhouse effect of the use of fossil fuels, as well as the high cost and depleting reserves [31]. However, in Ghana, there is a gradual decrease in the use of biomass resources and an increase in the use of petroleum products as a primary source of energy. Figure 2-8 shows the percentage share of primary energy consumption by fuel type in Ghana from 2000 to 2014.

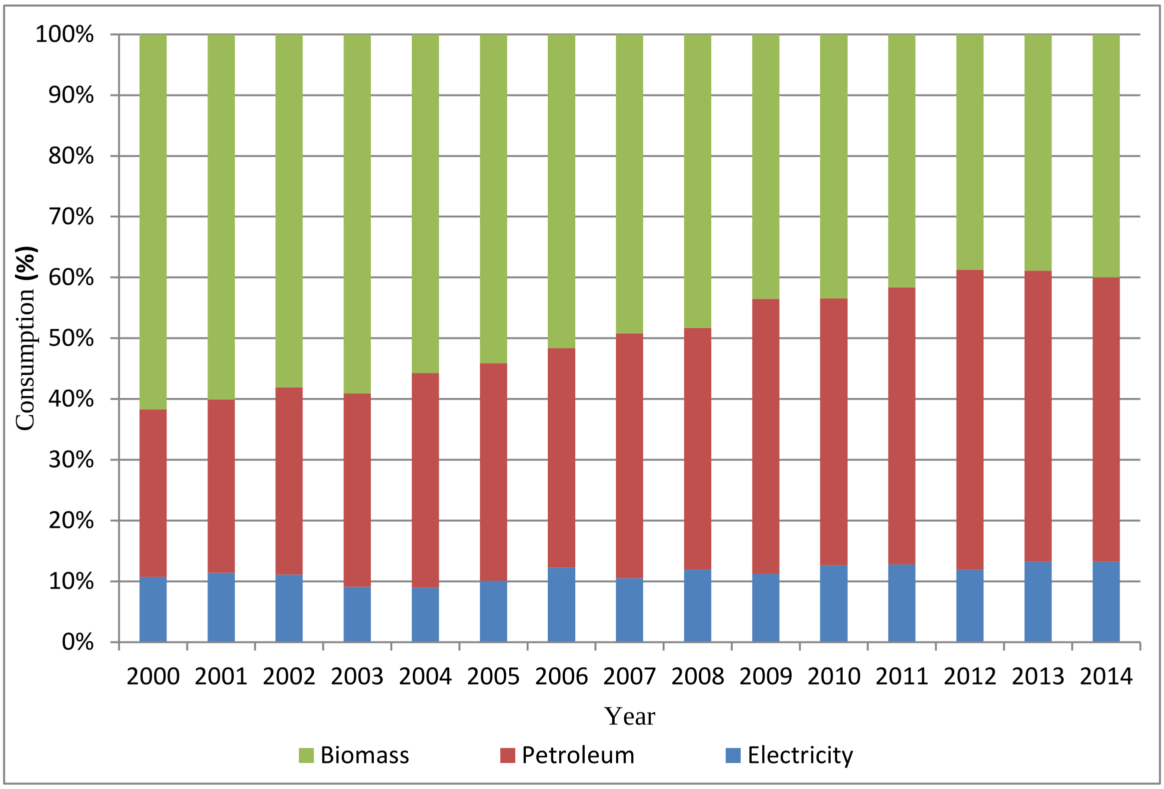


Figure 2-8 Trend in final energy consumed [3, 15]

Biomass, particularly from plants, absorbs carbon dioxide from the atmosphere to form energy during its growth. This carbon dioxide is later released back into the environment when the biomass is rotting or during combustion [32]. This implies the use of biomass in the generation of electricity will result in a near net zero carbon dioxide emission.

A comprehensive review of biomass resources in Ghana presented in [31] shows enormous potential of biomass for the production of electricity. It is estimated that about 4.8 million tonnes of crop residue was produced in 2008 alone. This has a potential to generate 75 Tera TJ of energy [31]. Logging and wood processing residues for the same period was also estimated to be about 616,000 tonnes, while 760,000 tonnes of municipal solid waste (MSW) or approximately 2000 tonnes per day was generated in the capital Accra alone in the same year [31]. Ofori-Boateng [33] therefore concluded by stating that even though the construction cost of plants to convert MSW into electricity are high, it is highly feasible to consider MSW as an alternative to produce power in Ghana.

Arthur et al. [34] studied the potential of biogas as a potential renewable source in Ghana. Their study also confirmed the availability of sufficient biomass resources with the potential for biogas production. Biogas can be used as a substitute to wood fuel for domestic applications and fossil fuels for industries.

Several institutions and households, especially in urban centres have installed their own biogas plants. Notable biomass power plants installations in the country are presented in Table 2-3. These biogas installations consist 82% fixed-dome and 8% water-jacket floating-drum digesters [35].

Table 2-3 Notable Biomass combined heat and power plants in Ghana [4]

Location	Installed capacity (kW)	Average annual production (GWh)
Kwai oil mills	420	1.50
Benso oil mills	500	1.9
Twifo oils mills	610	2.1
Juaben oil mills	424	1.5

Bensah and Brew-Hammond [35] conducted a review on these installations. Their findings indicate that only 44% of the 50 plants surveyed were found to be working properly. The rest were either not working or abandoned. The study further identified sanitation as the main reason for the installation of the biogas plants. They therefore recommended the development of national biogas programmed to focus on sanitation, energy and fertilizer production to encourage the development of this resource

Aside from the conventional sources of biomass, the cultivation of energy crops, such as eucalyptus, has also been established as a major source of biomass for power generation in Ghana. This view was highlighted in the strategic national energy plan of Ghana [4] that 150 000 hectares of eucalyptus plantation can fuel a 300 MW capacity steam power plant capable of generating 2100 GWh of power per year at an efficiency of 25% and availability of 80%.

2.5 OPERATIONAL STRUCTURE OF GHANA POWER SYSTEM

The power system of Ghana can be grouped under three main categories that are managed by different public institutions as illustrated in Figure 2-9, which shows the organisation structure of Ghana's electricity sector

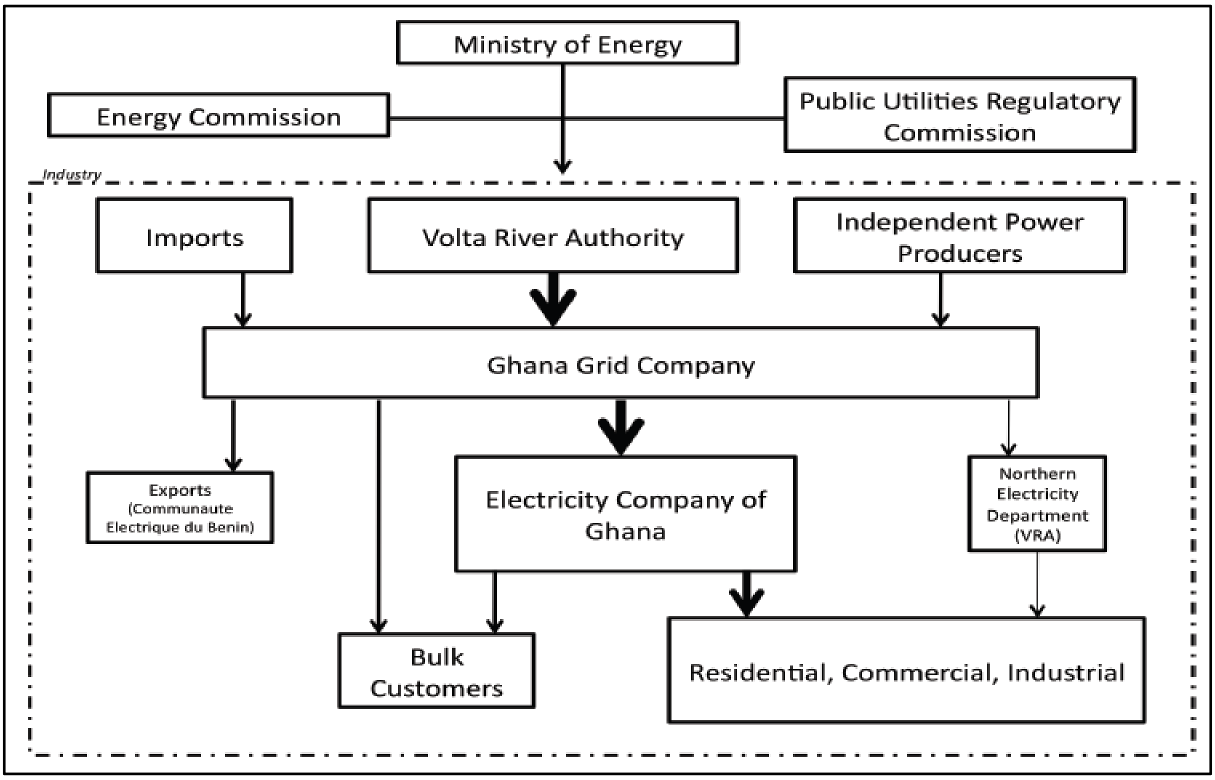


Figure 2-9 Operational sector of Ghana power sector [155]

2.5.1 Regulatory and Monitory

2.5.1.1 Ministry of Energy

The ministry of Energy is responsible for the formulation, implementation, monitoring and evaluation of power sector policies in Ghana. It is headed by a sector minister who has cabinet status and is supported by public institutions including the energy commission in the execution of its mandate.

2.5.1.2 Energy Commission Ghana (EC)

The EC is made up of seven commissioners appointed by the president of the republic of Ghana in consultant with the council of state. The commission is mandated by Act 541 of 1997 "to regulate and manage the utilisation of energy resources in Ghana and co-ordinate policies in relation to them" [36]. The commission advises the government on energy policies through policy recommendations to the ministry of power. The commission is also mandated to licence Independent Power Providers (IPP) for wholesale supply of electricity and natural gas, and to promote the utilization of indigenous energy resources as well as promoting efficient use of electricity, natural gas and petroleum. The EC, Ghana is also expected to formulate and enforce performance standards for utility providers [37].

The enactment of the renewable energy act, 2011, Act 832 [38] further mandates the commission to build indigenous capacity in renewable energy and to help diversify and improve access to electricity using RET.

2.5.1.3 The Public Utility Regulatory Commission (PURC)

The PURC is an independent body responsible for providing guidelines for Charges for the country's utility companies. This includes the provision of electricity, water and natural gas pipeline tariff as well as aggregate gas prices [39]. The PURC was established in October 1997 under the public utilities Act 538 of 1997. The commission is also responsible for approving rates for bulk purchase of power from renewable sources.

2.5.2 Generation

VRA, BPA and IPP are responsible for the generation of power in Ghana. The VRA provides 74% of the installed capacity in 2014, while BPA responsible for the Bui hydroelectric power plants provides 14%. The remaining 12% is provided by IPP who manage the Tema Cenit Thermal Power Plant (TCTPP) and Sunon-Asogli thermal plant [3, 40].

2.5.2.1 Volta River Authority (VRA)

VRA was established under the Volta power development act, Act 46 on April 26, 1961 with a mandate to generate, transmit and distribute power in Ghana [40]. However, following a re-structuring over the years, VRA's role has now been restricted to generation with the establishment of Ghana Grid Company (GRIDCO) in 2005, which has taken the responsibility for transmission. The Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCO) are now responsible for distribution.

2.5.2.2 Bui Power Authority (BPA)

BPA was established in 2007 by an act of parliament, Act 740 and is responsible for the Bui hydroelectric project. The history of the Bui gorge for power generation can be traced to J. S. Zhuk Hydroprojeckt of USSR who undertook preliminaries studies in 1966. Feasibility studies by Snowy Mountains Engineering Corporation (SMEC) of Australia and Coyne et Bellier of France in 1995 established the Bui hydro project to be the most technical and attractive hydropower site after the already constructed Akosombo and Kpong projects. The Bui power project was however not constructed until after the establishment of BPA. The project was formally commissioned in December 2013 with an installed capacity of 400 MW.

2.5.2.3 Independent Power Providers (IPP)

Two IPP complete the providers for bulk generation in Ghana. The Sunon Asogli Power (Ghana) Limited which is partly owned by Shenzhan Energy Limited (60%) and China Africa Development Fund (40%) operates the Sunon-Asogli thermal power plant which has an installed capacity of 200 MW [40].

Cenit Energy limited, which operated the second privately owned power plant, is a wholly owned Ghanaian company. The company constructed the TCTPP with an installed capacity of 126 MW, and begun commercial operation in 2012 [41]

2.5.3 Transmission

GRIDCO manages the transmission system of Ghana. GRIDCO was established because of the re-structuring of the power sector by the Volta River Development (Amendment) act, Act 262 of 2005 and incorporated on December 15,

2006. The main functions of GRIDCO are to undertake economic dispatch and transmission of electricity and carry out transmission system planning [42].

2.5.4 Distribution

ECG and NEDCO who distribute power to the southern and northern parts of the country respectively, manage the distribution sector of the power system of Ghana. ECG is a state-owned company that is responsible for the distribution of power in the southern regions of the country namely Ashanti, Eastern, Central, Western Volta and Greater Accra. The company began as the electricity department in 1947 and later Electricity Division of the then Public Workers Department in 1962. It subsequently became ECG in 1967 by NLC decree 125 and was originally responsible for the distribution of power to all parts of the country until 1987 when NEDCO was created as a subsidiary of VRA to manage the distribution of power to the northern parts of the country [43]

2.6 SUMMARY

There is a clear need for the expansion of the generation capacity of Ghana to meet the increasing demand because of industrialization and population growth. This review focuses on the current generation capacity and the renewable resources available in Ghana that can be harnessed to augment the current generation. Ghana has a very high potential for the development of Solar PV, hydro, biomass and wind generation. The daily average solar radiation of 5.5 kWh/m^2/day, which occurs throughout the year provides an excellent opportunity for the development of both grid-connected and isolated PV systems in the country. There is also the need to exploit the identified potential sites for development of small and medium hydro systems. Wind energy and generation from biomass especially MSW also have a great potential in the country.

CHAPTER 3

LITERATURE REVIEW

This chapter reviews previous studies related to the field of study. The chapter is divided into four subsections: the first section examines the methodologies for power generation system planning, their types and categories; the second part examines studies that applied LEAP methodology.

3.1 Methodologies for Long -Term Energy Planning

Due to the diverse nature of future studies, wide varieties of approaches have been developed for this field [44]. The future is uncertain and can unfold in many ways. The scenario approach, which analyses possible developments into the future by considering alternatives, is one of the most widely used methodology by futurist.

The concept of scenario planning can be traced to early philosophers such as Plato and visionaries from Thomas More to George Orwell [45]. However, the concept of modern day scenario began after the Second World War, mainly for military strategic planning in the USA and France.

The term scenario as it is applied in strategic planning was pioneered by Herman Khan and was originally applied in military studies in the 1950s [45, 46]. The concept has since been applied in an increasing number of disciplines: Kahn and Wiener developed scenarios to explore the consequences of nuclear proliferation at the heart of the cold war [47], while Brewer applied the concept to explore policies for Europe forestry sector [48]. The Inter-Governmental Panel on Climate Change (IPCC) has applied this methodology for developing emission scenarios in its assessment reports [49].

The application of scenarios for energy studies was inspired by the work of Lovins, who developed scenarios for Soft Energy Paths (SEP) [50]. Most recent energy scenarios with continental focus include Energy Technology Perspectives [51], International Energy Outlook [52], Greenpeace's Energy Revolution [53] and World Energy Outlook [54]. At the national level, scenarios were employed for assessing alternative energy pathways in California [55], Venezuela [56], Korea [57], Panama [58] and most recently, for environmental assessment of energy production from landfill gas plants in Tehran [59].

Most of the early scenario studies were concentrated in the USA and France. This gave rise to three major techniques: the intuition logics school, probabilistic modified trends (PMT) school and La prospective. The first two were developed in USA while La prospective was developed in France [60].

Herman Kahn [47] proposed the intuition logics methodology during his work at the RAND (Research and Development) cooperation in the 1960s. This methodology is the most applied technique in scenario planning literature [45, 60]. Schwartz [61] and Van der Heijden [62] methodologies belong to this class of scenario planning [45]. The intuition methodology does not use mathematical algorithms and relies largely on the knowledge, commitment and skills of scenario developers [60]. This methodology has a lot in common with the SRI international methodology, which were developed in parallel [45, 60].

Probabilistic modified trends school was also developed at RAND cooperation from the works of Olaf Helmer and Ted Gordon [60]. Probabilistic modified trends incorporate two different methodologies: Trend-Impact Analysis (TIA) and Cross Impact Analysis (CIA). TIA makes use of independent forecast of key dependent variable, which is then adjusted based on probability and impacts of selected future events [45, 60, 63]. This method has been used in the field of health care futures and a number of US federal agencies including Department of Energy, Federal Bureau of Investigation and National Science Agency [60]. Gordon, Helmer and others developed CIA methodology at RAND cooperation in 1966 for Kaiser Aluminium [45, 60] . CIA stems from the principle that an event cannot be realistically forecast without considering the occurrence of key impacting factors. This methodology therefore captures the interrelationships between key influencing factors making use of a cross impact matrix [60]. Many proprietary methodologies including Interactive Future Simulations (IFS) and Interactive Cross Impact Simulation (INTERAX) have been developed to conduct cross impact analysis [60].

French philosopher, Gaston Berger developed the La prospective methodology for long-term scenario planning [45, 60, 63]. The La prospective or prospective thinking methodology develops idealistic direction to guide future action [60, 62] . Michel Godet enhanced this methodology between 1974 and 1979 when he oversaw France department of future studies. The methodology was further extended at *Conservatoire Nationale des Arts et Metiers* with the support of France Ministry of Defence and other national agencies [45, 60]. The methodology has been applied in a wide range of areas including environment, education, regional planning and urbanisation [60]. Table 3-1 compares the main features of the three methodologies.

The purpose of scenario activity is one of the most important determinants of its success [64]. The objective of PMT and La Probabilistic methodologies is usually to determine the most likely future development of a particular phenomenon. This is mostly one-off exercise making sense of particular phenomenon. On the other hand, the intuition logics methodology provided for continuous adaptation to describe future development of a phenomenon. Consequently, intuition logic methodology can be broad – from global perspective to national, and at the same time, focus on a specific situation. On the contrary, PMT and La probabilistic methodologies are generally narrowly focused [45].

Table 3-1 furthers shows differences in terms of their approach and type of scenario produced by the different schools of scenario planning. The intuition logic is qualitative in nature whereas PMT is quantitative. La prospective combines both intuition and PMT methodologies. The intuition logic methodology results in qualitative, narrative scenarios, which are supported by graphics. The scenarios produced by this methodology tend to have limited quantification. However, the PMT and La prospective methodologies are outcome oriented, making use of complex extrapolative forecasting simulations.

Significant difference also exists in the nature of the participants in the scenario process. While the PMT relies on internal experience practitioners, that of the PMT makes use of external consultants. The La prospective combines key individuals from within the organisation led by external experts. The use of external experts in the PWM and La prospective is particularly important with the use of sophisticated mathematical and computer models.

Table 3-1 Caparison of key features of scenario techniques [45, 60]

	Intuitive-Logics methodology	Probabilistic modified trend methodology (PMT)	La prospective methodology
Purpose	Multiple, from onetime activity appraising situations and developing strategy to an ongoing process that includes adaptive learning	Usually, onetime activity to strengthen extrapolative prediction and policy evaluation	Onetime activity that develops more effective predictions and policy evaluation
Perspective	Descriptive or normative	Descriptive	Mostly descriptive
Scope	Can be either broad or narrow, ranging from global, regional, country to a specific issue	narrowly focused on the probability and historical trend of impacting factors	Generally narrow scope but examines a broad range of factors within that scope
Methodology	Process Oriented approach - subjective and qualitative, relying on disciplined intuition.	Outcome oriented - objective, quantitative and analytical approach using computer based extrapolative and simulation tools	Outcome oriented - objective, quantitative and analytical approach making use of mathematical and computer modelling
Nature of team	Mainly internal - External experts are used to obtain their views for new ideas	Mainly external - Leading role of external expert using proprietary tools and expert judgments	Combination of internal and external expects- Led by r external expert with the support of internal personnel
Tools	Brainstorming, clustering, matrices and stakeholders' analysis	Proprietary – structural and actor analysis, Delphi, Multi-criteria analysis.	Proprietary trend – impact and cross impact analysis, Monte Carlo simulations
Starting point	Particular management decision, issue or area of general concern	Issues with detailed and reliable time series data	Specific phenomenon of concern
Scenario development	Defining scenario logic as organizing themes often in the form of matrices	Monte Carlo simulations to identify to create an envelope of uncertainty around focal issue	Matrices of sets of probable assumptions based on key variables for the future
Scenario output	Qualitative- set of equally plausible scenarios in discursive narrative form supported by graphics, with limited quantification	Quantitative – baseline case plus upper and lower quartiles of adjusted time series forecast.	Quantitative and qualitative-multiple scenarios supported by comprehensive analysis incorporating possible actions and consequences.
number	Generally, 2 to 4	Usually 3 to 6	Usually 3 to 6
Evaluation criteria	Coherence, comprehensiveness, internal consistency, novelty, supported by rigorous structural analysis and logics All equally plausible	Plausible and verifiable in retrospect	Coherence, comprehensiveness, internal consistency tested by rigorous structural and mathematical analysis; plausible and verifiable in retrospect

.

The analysis of the main features of the three main schools of scenario planning show clear differences between the three methodologies. However, a high degree of similarity was observed between LA prospective and PMT methodologies.

Different steps have been developed by the different schools to aid in developing scenarios. TIA, IFS and INTERAX are the most popular quantitative techniques for scenario development while intuition logic is qualitative. Table 3-2 compares the steps of scenario planning under the most common scenario methodologies to generic steps of scenario planning.

The analysis of the various steps adopted by different schools of scenario analysis shows that the most important step is to identify the problem. This is usually the first step that determines the focus of the scenario development process.

Each of the methodologies analysed in Table 3-2 underscores the need to identify key factors. This will help establish the scenario logic and determine the number of scenarios. There is no consensus on the best number of scenarios. However, many scenario experts agree that a greater number is often confusing and unworkable [44, 60, 61, 65] and less than two is point estimate forecast [65].

Table 3-2 comparison of steps of scenario techniques

Generic Steps	Intuitive logics	TIA	IFS	INTERAX
Topic	1. identify focal issue or decision	1. Identify key scenario drivers 2. create scenario space	1. Define and structure topic	1. Define issue and time period
Key decisions	2. identify key decision forces			2. identify key indicators 3. project key indicators
Trend extrapolation		3. collect time series data 4. prepare naïve extrapolation		
Influencing factors	3. Analyse key environmental forces	5. establish list of impacting events	2. Identify influencing areas	4. identify impacting events
Analysis of factors	4. Analysing the environmental forces	6. Establishing probability of events occurring over time	3. Defines descriptors; assign initial probabilities	5. Develop event probability distributions
Cross impact			4a. complete cross impact matrix	6. estimate impacts 7. complete cross impact analysis
Initial scenarios	5. Defining scenario logic	7. Modify extrapolation	4b. run the program 5. select scenarios for further study	8. Run the model
Sensitivity analysis			6. Introduce uncertain events and perform sensitivity analysis	
Detailed scenarios implications	6. fleshing out the scenarios 7. Analysing implications for key decision factors 8. Analysing implications for decision strategies	8. Write narrations	7. Prepare forecast 8. Study implications	

Table 3-3 provides a comparison of scenario selection approach and recommended number of scenarios highlighted by different researchers, adapted from [60].

Table 3-3 Summary of recommended number of scenarios and approaches for selecting scenario [60]

Source	scenarios number	Method of scenario selection
MacNulty [66]	3 – 4	Judgmental integration of trends and intuition
Linneman and Klein [67]	3 – 4	Select plausible combinations of key factors
Dator [68]	4	Developed alternative futures based on four scenario archetypes: continued growth, collapse, steady state and transformation
Becker [69]	3	Selects plausible combinations of key factors
Schoemaker [70]	More than 2	Identify key decision variables, trends, predetermined elements, and major uncertainties
Hicks and Holden [71]	4	Create scenarios entitled ‘more of the same’, ‘technological fix’, ‘edge of disaster’ and ‘sustainable development’
Schwartz [61]	4	Rank the focal issues and key factors on the basis of importance and uncertainty in a 2 by 2 matrix
Van der Heijden [62]	At least 2	Identify the driving forces, mega trends and critical uncertainties
Bradfield et al. (PMT) [45]	3 – 6	Quantitative trend analysis and use of expert judgment
Bradfield et al. (intuitive logics) [45]	2 – 4	Intuition, expert opinion, STEEP analysis, brainstorming Techniques
Inayatullah [72]	3 – 5	Develop scenarios through causal layered analysis
Bezold [73]	3	Develop scenarios for most likely, challenging and visionary possibilities

Some of the earliest developers of scenarios, Global Business Network (GBN) and Sanford Research Institute (SRI) recommend a limit of four scenarios by combining two hypotheses [60, 74]. This approach however, oversimplifies the scenario planning process, which may lead to non-consideration of important details. MacNulty [66] suggests that scenarios should be developed by judgemental integration of trends and intuition. Linneman and Klein [67] indicated that the number of scenarios should be 3 – 4 and should be constructed by selecting plausible combinations of key factors. Schwartz [61] stated four as the best number scenarios, which should be constructed by ranking focal issues and key factors based on importance and uncertainty in a 2 × 2 matrix. The number of scenarios and their implications is presented in Table 3-4 [60, 75].

Table 3-4 number of scenarios and their implications [60, 75]

Number scenarios	Implications
1	Most likely scenario, though convenient for strategic planning, will not yiel alternative options
2	Usually based on two extreme situations (optimistic and pessimistic), which are difficult to evaluate.
3	Recommended by many researchers but there is the risk of selecting the middle scenarios
4	Good cost benefit ratio
5	possible
Greater than 5	Possible, but high cost of drafting and evaluating large number of scenarios does not make them justifiable

It is evident from Table 3-3 and Table 3-4 that 3 – 5 scenarios is considered appropriate by most of the researchers. The analysis shows that few researchers propose the creation of less than three scenarios. Less than three cannot fully capture alternatives, while more than five is not desirable. The study therefore concluded based on literature that developing 3 – 5 scenarios are most appropriate for scenario planning.

The analysis clearly shows the diversity in scenario planning approaches. While there may be no mechanical method of scenario development [65], there are a some guidelines. These guidelines provide useful answers to key questions regarding scenario construction [61, 65].

1. Avoid assigning probabilities to different scenarios, because of the temptation to consider scenario with the highest probability. The goal of scenario analysis is to generate equally likely outcomes and not “most likely” outcomes. The use of probabilities in developing scenarios is thus misleading.
2. Appropriate names should be selected for scenarios to clearly illustrate the scenario logic

3. Good scenarios are both plausible and surprising. Such scenarios have the power to break old stereotypes and makers assume ownership.
4. Beware of ending up with three scenarios. There is always the tendency to identify the middle as the most likely scenario.
5. Scenarios should be limited to environmental forecast. They should not include plans.
6. Selection of scenario management team should be guided by the following three considerations.
   a. Ensure support and participation of highest level of management. There is the need to involve decision makers and implementers in the planning stage to ensure acceptability of the “finished product”.
   b. Include wide variety of divisions and functions should be represented.
   c. Select imaginative and open minded personnel.

This thesis therefore combined the three main techniques of scenario planning. A detailed description of the improved methodology is described in Chapter 4.

3.2 Computer Tools for Energy Planning

Energy planning is a multidisciplinary field. The energy planner will not only have to consider economic and technological parameters, but also, institutional, sociological and political issues [76]. Due to the diversity and complexity of the energy sector, wide variety of computer tools has evolved since the 1970s for energy systems analysis. While some computer tools provided models of complete generation systems, others focused on specific subsectors such as demand or supply.

A number of studies [77-82] have reviewed computer tools for energy planning and compared their performances. Hoffman and Wood [77] provided a review on the scope, application, methodology and content of energy models for future energy forecasting. Their review revealed that the state of research at the time, focused on integrating engineering models with behavioural models. The aim of the integration was to produce hybrid-integrated systems with improved modelling capabilities.

Beaujean et al. [78] surveyed global and international energy models. Their survey was a follow up of Charpentier [83, 84] and Charpentier and Beaujean [85], which identified 144 national and international models. These models were compared under categories including scope, methodology, purpose and performance. The study revealed that all the models were developed and applied mostly in the USA and Western European countries.

Rath-Nagel and Voss [79] provided a surveyed and compared the different categories of the most popular energy models. The study categorised models under two broad classes: energy systems models and energy-economic models. Energy systems models reviewed include BESOM (Brookhaven Energy System Optimisation Model), EFOM (Energy Flow Optimisation Model), MARKAL (Market Allocation) and MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental impacts). The energy economic models were further divided into integrated models and model sets. Integrated models discussed included ETA-MACRO (Energy Technology Assessment and Macroeconomic growth), SRI (Stanford research institute), Hudson-Jorgenson, ESPM (Energy Supply Planning Model), PIES (Project Independence evaluation system), while DRI-BROOKHAVEN (combination of Hudson-Jorgenson and BESOM models), and IIASA (International

Institute of Applied Science Analysis) were considered under model sets. The study further discussed in details, the content and applications of one model which is representative of each group (MARKAL, ETA-MACRO, IIASA). Their review concluded by providing a detailed list of unresolved modelling issues and provided suggestions for possible improvements of the computer tools. (Brief descriptions of the selected energy models are provided in Appendix A)

A more detailed analysis of computer tools for modelling the energy systems of developing countries is presented in Urban et al [80]. Urban et al. [80] identified a number computer modelling tools that are commonly used for energy systems analysis. These include AIM (Asian-Pacific Integrated Model), ASF (Atmospheric Stabilisation Framework), TIMER (Targets-Image Energy Regional Model), LEAP, MARIA (Multiregional Approach for Resources and Industry Allocation model), MARKAL, MiniCAM (Mini Climate Assessment Model), Powerplan, RETScreen (Renewable Energy Technology Screening model), SGM (Second generation Model) and WEM (World Energy Model). Urban et al [80] analyses identified four of the models to be most suitable for modelling the energy systems of developing countries. These tools include LEAP, MESSAGE, RETScreen and WEM. The Urban et al. [80] review, just like that of an earlier review by Pandey [86], however, identified the inadequacy of all the tools to capture all dynamics of energy systems and economics of developing countries. Urban et al [80] further identified these deficiencies and provided proposals to enhance their capabilities.

A subsequent review of 37 computer tools for analysing renewable energy integration into various energy systems was presented in Connolly et al [81]. This review provided a comprehensive description of each of the tools they considered. Their study further analysed each of the tools using nine point criteria: type of tool;

type of analysis (geographic area, scenario, timeframe, time step); energy sectors considered (electricity sector, heat sector, transport sector) and renewable energy penetration simulated. The Connolly review shows that, of all the computer tools analysed, only COMPOSE (Compare Options for Sustainable Energy) , EnergyPlan (Computer model for energy system analysis) , ENPEP-BALANCE, IKARUS, INFORSE, LEAP, MARKAL/TIMES, Mesap PlaNet (Modular Energy-System Analysis and Planning Environment Planning Network), MESSAGE, NEMS (National Energy Modelling System) AND PRIMES can fully model electricity, heat and transport technologies. Their analysis further revealed that only five of the tools: EnergyPlan, INFORSE (International Network for Sustainable Energy), LEAP, Mesap Planet have been applied for assessing 100% renewable generation. The study also compared the number of users worldwide in terms of downloads/sales. RETScreen, HOMER, LEAP, BCHP screening tool, EnergyPRO were identified to have very high number of users, while EnergyPlan, MARKAL/TIMES, MESSAGE and WASP (Wien Automatic System Planning Package) were among models with high number of users.

Bhattacharyya [82]compared the performance of alternative modelling approaches based on the following criteria: geographic coverage; activity coverage; level of disaggregation; technology covered; data requirement; skills requirement; non power sector modelling capability; new technology addition; informal sector; time horizon and computing requirement. Modelling approaches considered in this study included bottom-up, optimisation, bottom up accounting, top down econometric, hybrid and electricity planning. The study then focused on bottom up and hybrid approaches and compared specific computer tools from both groups. Bottom up tools compared included RESGEN (Regional energy scenario generator), EFOM

(Energy Flow Optimisation Model), MARKAL, TIMES, MESAP and LEAP. While, that of the hybrid tools included NEMS, POLES (Prospective outlook on long-term energy systems) and WEM. The study concluded that accounting bottom up tools are most suitable for developing countries because of their flexible data requirement and focus on scenarios rather than optimal solution.

The purpose of this section of the review was to identify the most suitable computer tool for analysing the long-term development of the generation system of Ghana. The review did not particularly identify a tool to be the best for modelling the generation systems of developing countries. All the systems have their merits and limitations. Both [86] and [80], whose studies focused solely on computer tools for developing countries, agreed that none of the tools fully capture the dynamics of developing countries. Bottom up accounting software, however, were identified to be the best for long term energy studies in developing countries [80, 82].

The review also revealed that most of the energy modelling tools were built and applied in developed countries [80]. However, there is wide variation between the energy systems of developed and that of developing countries including Ghana. The energy systems of developed countries are characterised by constantly matching demand and supply, low transmission and distribution (T&D) losses, universal access and similar rural and urban energy consumption characteristics, relaying largely on modern sources of energy. Developing countries on the other hand rely on traditional fuels such as biomass to meet their energy needs [80, 82]. They have inefficient energy systems mostly characterised with supply shortages. Other challenges of energy systems of developing countries include rapidly growing demand, high level of transmission and distribution losses, under financed power companies coupled with low consumer prices. High variations also exist between the energy requirements of rural and urban settlements [80, 82, 86].

Based on these findings, a further assessment was undertaken to select an appropriate tool, most suited for the Ghanaian situation. An adequate computer tool for modelling the energy systems of developing countries should reflect specific problems in their energy sector [87]. The following criteria was therefore adopted for comparing the selected computer tools in this thesis [80]: approach, methodology, geographic coverage, activity coverage, technology coverage, documentation, urban, rural divide. The three tools selected (MESSAGE, LEAP, TIMES/MARKAL) was based on three essential criteria [80-82]:

(i) the popularity of the tool in terms of usage

(ii) widely cited in the literature

(iii) suitability for scenario analysis.

Table 3-5 shows the extent to which these characteristics of energy system of developing countries are addressed by the selected models.

Table 3-5 Comparison of most widely used energy planning tools

Energy tools	Tool		
	MESSAGE	LEAP	TIMES/MARKAL
Purpose	Energy supply, economy, climate model	Energy, economy, environmental modelling tool	Energy, economy, environmental model
Methodology	Optimisation	Accounting, simulation, optimisation	Optimisation,
Geographic coverage	Global and international	Local to national to global	Local, regional, national or multiple countries
Technology coverage	Extensive	Menu of options	Extensive
Documentation	Good	Extensive	Good
Urban, rural divide	Implicitly modelled	Explicitly modelled	Explicitly modelled
Data requirement	Extensive	Extensive but can work with limited data	Extensive
Skill requirement	high	limited	Very high
Economic transition	Not explicitly	Covered through scenarios	Can be covered
Cost	Free for academic use/ simulators must be purchased	Commercial/ free for students and developing countries	Commercial

Source: [80-82, 87]

The three selected models are all applied for energy, economy and climatic analysis which is in line with the scope of this thesis. However, while LEAP and TIMES are applied for the entire energy sector, MESSAGE is designed for the supply sector of the energy system. LEAP is also superior in terms of methodology. LEAP performs both simulation and optimisation, while that of MESSAGE and TIMES/MARKAL methodology leads to the development of optimal systems. Optimisation process assumes the availability of adequate financial and other resources to develop systems to match demand. This is however not practical in the case of developing countries where the availability of funds is a major issue.

Models that do not recognise the rural urban dichotomy present in developing countries would not adequately represent their energy systems [87]. LEAP and TIMES explicitly modelled this characteristic which is not directly captured by MESSAGE. The rural energy system is complex with the use of non-commercial fuels such as animal droppings and firewood. Even though monetary these traditional fuels are difficult, there is the need to capture them when analysing energy systems of developing countries. This is because they form an integral component of the energy requirements, especially, the rural communities of developing countries including Ghana.

The problem of lack of adequate and consistent data in developing countries [87] affects the capabilities of MESSAGE and TIMES, which require extensive data. To improve energy planning therefore, there is the need to urgently invest in the collection of data and making it available for energy planners. In the interim, the LEAP model will serve as the best choice, since its simulation modelling requires comparatively less data requirement.

In view of the above observations, LEAP model was selected for modelling the generation system of Ghana. The extensive documentation coupled with low skill requirement in using the LEAP tools are additional advantages of the tool.

3.3 Applications of LEAP for Energy Planning Studies

The Long-range Energy Alternatives Planning (LEAP) system developed by Stockholm Environmental Institute (SEI) is a widely used energy modelling tool for energy policy analysis and GHG emission mitigation studies [109]. A detailed description of the LEAP model is presented in section 4.2.

LEAP was first developed in 1980 to provide a flexible tool for long-range integration energy planning for the Beijar Institute’s Kenya fuelwood project [110]. Today, the software is used by more than 26,000 users, which includes academics, government and non-governmental agencies in over 190 countries [108].

Table 3-6 Summary of literature on application of LEAP tool

Study	Focus	Scope	Scenarios	Key features/results
Kumar et al., 2003. [88]	Greenhouse mitigation potential of biomass energy technologies (BET)	Country (Vietnam) 1995 - 2020	Seven scenarios: Base case, no mitigation; replacement of coal stoves by biomass; LPG and kerosene stoves by biogas stoves; replacement of gasoline by ethanol in cars; replacement of coal by wood in industrial boilers; substitution of fossil fuel power plants by package of BET and integrated.	Evaluated BIGCC based on wood and bagasse, direct combustion based on wood, co-firing power plants, Stirling engines and cooking stoves.
Shin et al., 2005. [89]	Impacts of landfill gas electricity generation in terms of cost and GHG emission	Korea 2005 - 2015	Three scenarios groups: Base case, technological improvement and maximum LFG utilization	Alternative scenarios based on technological improvement. LFG is substituted for nuclear, coal steam, combined cycle and oil steam. Technological expansion resulted in increased electricity output, decrease in cost and reduction GWP. LFG utilization reduces GWP up to 75%
Davoudpour and Ahadi, 2006. [90]	Evaluated impacts of price reform and efficiency on energy carriers' consumption and GHG mitigation	Iran 2000 - 2010	Three scenarios: bas scenario, business as usual and management	Efficiency programs would not be effective without price reforms. Proposes comprehensive policy for fuel price, de-subsidizing and energy efficiency programs in the national context
Mulugetta et al., 2007. [91]	Evaluated policy options for power generation sector	Thailand 2002 – 2022	Three Scenarios: BAU, no new coal, Green futures	High projected future demand resulted in higher emissions in all scenarios. Improvement in carbon intensity (tonnes/MWh) in all scenarios. Alternative scenarios diversified the fuel mix to include local resources such as biomass, wind and solar. The costs of alternative scenarios are marginally higher than BAU
Zhang et al., 2007. [92]	Estimated environmental cost of fired electricity generation.	China 2003 – 2030	Five scenarios: BAU, coal replacement, advance technology adopted, current abatement policy, further abatement policy	External cost may reduce 24-55% with three energy policies and further 20.9-26.7% with two environmental policies. Total external cost reduction of 58.2 is achievable
Papagiannis et al., 2008. [93]	Analysed application of intelligent demand side management system.	15 European Country (2006). 2000 - 2025	Four Scenarios: Reference, low penetration, medium penetration, high penetration.	1 – 4% reduction in primary energy, 1.5 – 5% in CO2 reduction and 2 – 8% savings in investment cost. Justified the use of innovation devices and global energy saving policies

Study	Focus	Scope	Scenarios	Key features/results
Giatrakos et al., 2009. [94]	Plan conventional plant upgrades and liquefied natural gas transition to meet EU RES directive	Island of Crete	Two scenarios: BAU, Extended DSM loads	RES penetration of more than 30% is achievable by 2020. RES implementation with partially demand restriction could contract the island's environmental footprint.
Dementjeva and Siirde, 2010. [95]	Tested the suitability of LEAP for examining Estonian energy system	Estonia 2008 – 2035	Eight scenarios: reference, low growth, high growth, nuclear capacity, renewable energy, hybrid, low growth hybrid, high growth hybrid.	Demonstrated the adequacy of LEAP for elaborating scenarios for entire generation system as well as sub sectors.
Mondal et al., 2010. [96]	Forecasted future demand based on three GDP growth rates and compare with official projections	Bangladesh 2005 – 2035	Three scenarios: low, Average and High GDP growth scenarios.	Made used of bottom-up approach and interrelates demand with population, GDP growth, urbanization and technology change. Confirm the suitability of LEAP for developing good electricity demand.
Mustonen, 2010. [97]	Effect of energy consumption to the attainment of MDG in rural settings	Lao (Single village)	Three scenarios: residential demand, income generation, public services	Compares the benefits of the scenarios in achieving the 6 MDG. Electrification increases lighting efficiency and reducing lighting cost. Improved income generation with electrification
Phdungsilp, 2010. [98]	Examined options for energy and	Bangkok 2000 – 2025	Multi-criteria approach: resource use, environmental loading, financial and economic, social and practical (political)	Highlights steps required to promote low carbon development. Shift from private to mass transit systems significantly reduces demand and carbon emissions.
Shabbir et al., 2010. [99]	Analysed urban transportation to determine demand and status of emission	Rawapindi and Islamabad 2000 – 2030	Four scenarios: BAU, population reduction, public transport, natural gas vehicle	Determined the optimal transport policies, which reduces future consumption growth and air pollution.
Qingyu et al., 2010. [100]	Estimated fuel consumption in vehicles	China 2007 – 2030	Three scenarios: BAU, advanced fuel economy, alternative energy replacement	Government energy conservation policies in the vehicular section are viable with effective implementation
Dagher and Ruble, 2011. [101]	Modelled future paths for Lebanon generation system	Lebanon 2006 – 2050	Three scenarios: baseline, renewable energy, natural gas	Superior economic and environmental performance of alternative scenarios. Discuss potential barriers to the implementation renewable energy sources.
Flores et al., 2011. [102]	Presented various energy diagnoses and potential for changing the generation mix	Honduras 2005 – 2030	Two scenarios: baseline, desired scenarios	Identified large dispersion in decision making and management of energy resources. Proposed new structure and installation of additional 3000 MW capacity

Study	Focus	Scope	Scenarios	Key features/results
Yophy et al., 2011. [103]	Compared future demand and supply options as well as GHG emissions.	Taiwan 2008 – 2030	Five Scenarios: BAU, Government, financial tsunami, renewable energy technology, All	Most effective energy policy is demand side management, through aggressive adoption of energy conservation policies and reasonable energy pricing
Takase and Suzuki, 2011. [104]	Described current issues and future development of demand and supply sectors	Japan 2007 – 2030	Five scenarios: BAU, nuclear minimum, nuclear maximum, National alternatives and nuclear minimum, national alternatives and nuclear maximum	Describe alternative pathways with emphasis on nuclear and GHG emission abatement
Tao et al., 2011. [105]	Simulated low carbon development	China 2005 – 2050	Three scenarios: base, low carbon, frustrated low carbon	Decrease in CO2 emission due to improved intensity. Fuel switch and renewable energy penetration positively affect emission reduction
Feng and Zhang, 2012. [106]	Analysed future trends in demand, structure (energy mix) and carbon emission	Beijing 2007 – 2030	Three scenarios: BAU, basic policy, low carbon	Identified building and transportation as promising areas for effective energy consumption control. Provided insight into Beijing's energy future and provided guidelines for future low carbon development
Bautista, 2012. [56]	Analysed present and future energy situation	Venezuela 2006 – 2050	Four scenarios: BAU and three sustainable energy scenarios	Show adequate resources for sustainable energy development. Energy efficiency is easiest path to reduce GHG emissions
Roinioti et al.,2012. [107]	Build future scenarios to explore RES development	Greece 2009 – 2030	Four scenarios: BAU, high emissions-high growth, high emissions-low growth, low emissions-low growth	Large scale RES integration will positively impact employment and economic activities. It will also consolidate energy security by making use of local resources and contribute to climate change abatement.
Aliyu et al., 2013. [108]	Analysed current and future expansion plans	Nigeria 2005 – 2030	Four scenarios: reference, high-growth, optimistic I, optimistic II	Provided environmental ramifications of power sector reforms. Provided potential environmental impacts of construction of nuclear plant in one of the potential sites
Cai et al., 2013. [109]	Simulate different electric power planning policies	China 2010 – 2050	Three scenarios: baseline, carbon capture and storage CCS), nuclear priority	Protecting the security of nuclear plants, control and monitoring of CCS and steadily advance clean power technologies will lead to stable energy conservation and emission reduction
Pan et al. 2013. [110]	Long term combined energy consumption structure and demand development	Beijing 2010 – 2020	Two scenarios: low, medium energy	Adjustnmne in demand structure can effectively relieve pressure on supply and reduce emission of pollutants anf GHG emission

Study	Focus	Scope	Scenarios	Key features/results
Park et al., 2013. [57]	Provide alternative energy pathways for Korea	Korea 2008 – 2050	Three scenarios: baseline, new government policy, sustainable society	Discounted cumulative cost of sustainable scenario will be 10 – 20% higher than the other scenarios. Emissions will however be about 80% lower
Halkos et al., 2014. [111]	Investigate how European and national targets are reflected in economic and environmental terms	Greece 2010 – 2030	Five Scenarios: base line, European target 2020, European target 2030, IMF optimistic, OECD conservative	Substantial shift in generation mix in all scenarios by 2030. European target 2030 results in highest emission savings but most expensive.
Kale and Pohekar, 2014. [112]	Analysis of demand and supply scenarios and discuss policy implications	Maharashtra (India) 2012 – 2030	Three Scenarios: BAU, Energy conservation, renewable energy	Substantial increase in demand in all scenarios. Discuss policy implications of scenarios in terms of energy, environmental influence and cost.
McPherson and Karney, 2014. [58]	Quantitative analysis of current and explores future scenarios	Panama 2012 – 2026	Four Scenarios: BAU and three alternative scenarios	Made used of Schwartz methodology. Three alternative scenarios compared to BAU. Scenario 1 encourages climate mitigation without incorporating new technologies in the generation mix. Scenario 2 maximizes resource diversity. Scenario 3 minimizes global warming potential.
Perwez and Sohail, 2015. [113]	Analysis of financial and environmental perspectives of alternative scenarios	Pakistan 2012 – 2030	Three Scenarios: BAU, New coal, Green future scenario	. Green scenario is more attractive in terms of emission reduction but have the highest capital cost. Provided recommendations in economic and environmental aspects of the generation system of Pakistan.
Mahumane and Mulder, 2015. [114]	Evaluate the impact of anticipated surge in exploration of natural resources on energy demand and supply.	Mozambique: 2011 – 2030 Reference 2000 – 2011	Four scenarios	Energy production is expected to increase up to six fold by 2030.
Wu and Peng, 2016. [115]	Analysis of carbon emissions from the power sector	China 2012 – 2030	Six scenarios for forecasting national demand and two carbon minimization scenarios	more stringent criterion on industrial power intensity and large capacity and efficient clean energy technologies accelerates carbon reduction
Emodi et al., 2017. [116]	Explore future energy demand, supply and associated GHG emission	Nigeria 2010 to 2040	Four scenarios: reference, low carbon moderate, low carbon advanced, green optimistic	More aggressive policy intervention would lead to a decrease in energy demand and GHG emissions in 2040. Presented cost-benefit and energy system analysis

This review found thirty-two studies, which have applied LEAP for scenario analysis in different countries. Table 3-6 outlines the various studies in terms of their focus, scope, number of scenarios and key features.

Kumar et al. (2003) [88] assessed the GHG mitigation potential of selected Biomass Energy Technologies (BET) in Vietnam. The BET technologies selected include Biomass Integrated Gasification Combined cycle (BIGCC), direction combustion, co-firing and stirling engine plants. Based on these selected BET, the study developed seven scenarios: Base case, no mitigation; replacement of coal stoves by biomass; Liquefied Petroleum Gas (LPG) and kerosene stoves by biogas stoves; replacement of gasoline by ethanol in cars; replacement of coal by wood in industrial boilers; substitution of fossil fuel power plants by package of BET and integrated. The results of their study show that substitution of coal stoves by biogas stoves result in extra cost due to comparatively higher cost of wood. The same phenomenon was observed with the replacement of kerosene and LPG cooking stoves with biomass. The replacement of coal by wood was also found not to be attractive due to high cost of wood in Vietnam. However, the study revealed that substitution of fossil fuel plants by packages of BET is the most promising of the scenarios. This option, unlike all the other scenarios, has negative abatement cost and will result in mitigation of 10.83 Mt of CO_2. These results suggest that adopting of various BET for power generation will have higher mitigation benefits than fuel substitution in other sectors.

An analysis of the economic and environmental impacts of an intelligent demand management system was performed by Papagiannis et al (2008) [93] in the 15 European countries (as at 2008). The demand management system referred to as Energy Consumption Management System (ECMS) is an integrated system, which aims at rationalizing electricity consumption. Their study examines three penetration rates of ECMS: low, medium and high. These penetration rates represented the expected market penetration. Their findings show a reduction of 1 – 4% in primary energy, 1.5 – 5% in CO_2 emission reduction and 2 – 8% investment cost savings across the 15 European countries. These results justify the application of innovative devices for demand side management may be attractive to end users. The acceptance of these devices will consequently help in the implementation of global energy saving policies.

Four critical factors: per capita GDP, energy structure, energy consumption and CO_2 emission were applied in Tao et al. (2011) [105] to measure low carbon development in China. The study simulated three scenarios: base, low-carbon and frustrated low-carbon, to serve as an important reference to guide low carbon development in China up to 2050. The results of the study show that considerable decrease in CO_2 emission is achieved with improvement in energy intensity. The study also revealed that high renewable penetration and fuel switching have a positive effect in decreasing CO_2 emissions. This means that based on the Chinese conditions, a low-carbon economy can be achieved by adjustment in industrial structure, use of clean coal technologies and improvement in efficiency.

Domestic energy requirement of most developing countries are mainly achieved using biomass, which has human and environmental consequences. Access to clean and stable electrical power is thus essential for sustainable development. Aliyu et al. 2013 [108] examined the current electricity generation and future expansion trends in Nigeria up to 2030. This study examines pathways to promote clean and stable power generation in Nigeria. The study also investigated the environmental impacts of a candidate nuclear plant in the country.

Emodi et al (2017) [116] undertook a study similar to Aliya et al. [108], to explore the future demand and supply and associated GHG emissions in Nigeria. Emodi et al [116] study further examines the impact of different energy policies on the Nigeria power generation system. This was achieved using four scenarios: reference, moderate low carbon, advanced low carbon and green optimistic scenario. The results show that the introduction of more aggressive policy intervention in Nigeria will lead to decrease in demand and GHG emissions. These findings suggest that to achieve low carbon development in Nigeria, various policy options to promote the use of clean energy resources should be explored.

The purpose of this section of the review was to obtain information on the application of LEAP tool world for energy planning studies. This provided an insight on the capability of the tool and information to guide its application in this current work. The following observations were made based on the literature review

- LEAP is used for medium to long term energy modelling. Almost all the studies reviewed used a forecast period of between 10 to 50 years. Most of the studies also included historical years between 2 – 5 years to test the model ability to replicate historical data.
- The LEAP methodology is versatile and includes several approaches for both demand side and supply sides. However, on the demand side, most studies adopted the bottom-up approach.
- The review further revealed that many studies focused on GHG mitigation by demand side management strategies, while maximising diversification of the energy mix [90, 93, 94, 96-98, 105, 106, 110]. Others developed strategies for GHG mitigation by focusing on supply side [58, 91, 113]

This study examines GHG mitigation by imposing both demand and supply side strategies for the Ghana energy system. Similar studies in this category include Yophy et al. [103] for Taiwan, Mahumane and Mulder [114] and Emodi et al. [116] for Nigeria. Based on the synthesis of the literature, future energy demand and supply scenarios for Ghana were developed using the LEAP model.

3.4 Summary

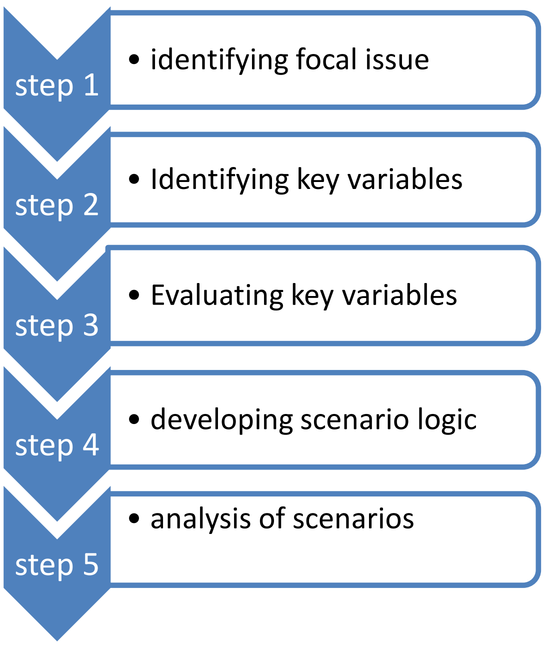
There are many different types of scenario approaches ranging from intuitive to analytical. The different methodologies produce scenarios with varied complexities. There is no single "appropriate" method of scenario planning. The type adopted depends largely on the context of the study and expertise of the scenario team. The diversity in scenario planning makes room for flexibility for futurist. Each approach has its advantages and limitations. Based on the analysis of the different methodologies, this study developed a hybrid method, which makes use of the strengths of both the intuitive and analytical approaches. A description of the developed framework, which is an adaptation Schwartz methodology, is described in Chapter 4. The developed framework reduced the planning steps proposed in the Schwartz framework from eight to five and incorporates quantitative analysis.

CHAPTER 4

MODELLING OF GENERATION SYSTEM OF GHANA

4.1 SCENARIO FRAMEWORK

Due to the diverse nature of the application of this technique, various methodologies have been developed to guide scenario development. The scenarios in this study were developed to explore possible developments in the generation system of Ghana using an adaptation of the Schwartz scenario planning methodology [61]. Schwartz method is one of the most comprehensive methods of scenario building and has been applied widely in literature for scenario planning. An adaptation of Schwartz approach was used in developing scenarios to explore energy pathways in California [55]. A framework developed to support environmental decision-making was also based on this methodology [117]. Schwartz approach was also employed for analysing alternative generation pathways for the Panama's electricity sector. Figure 4-1 shows the framework used in the development of the scenarios in this study.



Step 1: Identifyir Figure 4-1 Framework for Scenario development [61] narios begins with identification of the main topic or idea and building outward. The focal point of this thesis was to explore the suitability of high integration of RET in Ghana.

Step 2: identification of key variables: the second stage involves listing the key variables influencing the outcome of the decision as well as the social, economic, political, environmental and technological forces that influence the key factors. Examples of key variables that influence the generation sector of Ghana includes energy security and reliability, types and potential of RET, cost of fuel, technical capacity, cost of technologies as well as economic and population growth rates.

Step 3: Evaluating key variables: the next stage involves ranking of key variables making use of two criteria: (i) degree of importance and (ii) degree of uncertainty. The idea is to identify two or three of the most important and uncertain variables from the ranking. Figure 4-2 presents the ranking of the key variables influencing the generation system of Ghana.

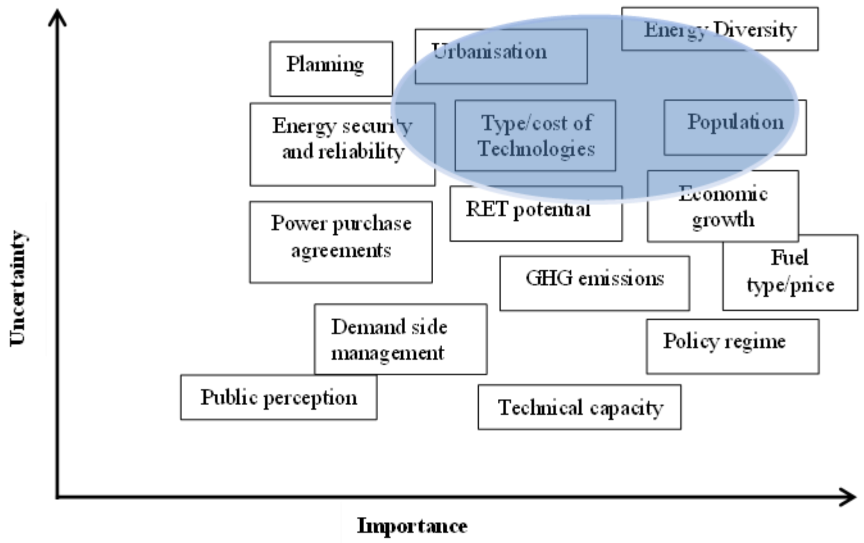


Figure 4-2 Evaluating driving forces in generation system of Ghana [55]

Step 4: Developing scenarios logic: The scenario logic is then developed based on the ranking exercise. The key is to end up with few policy scenarios with clear policy direction to assist decision makers. The scenarios are developed to revolve around the key variables. Finally, they are enriched by adding details making use of the other key factors. This is done by making use of each key structure or trend of the ranking.

Step 5: Analysis of the scenario: the final stage of the scenario methodology used in this paper involves an analysis of the various scenarios in order to elaborate future generation development proposed by the various scenarios and their consequences. This involves the translation of the qualitative narration into quantitative data and assessment using the LEAP tool.

4.2 OVERVIEW OF THE LEAP MODEL

LEAP interface is structured under seven different views by means of graphical icons: Analysis, Results, Energy balance, Summaries, Overviews, Technology database (TED) and the Notes views. Figure 4-3 shows a graphical representation of LEAP model.

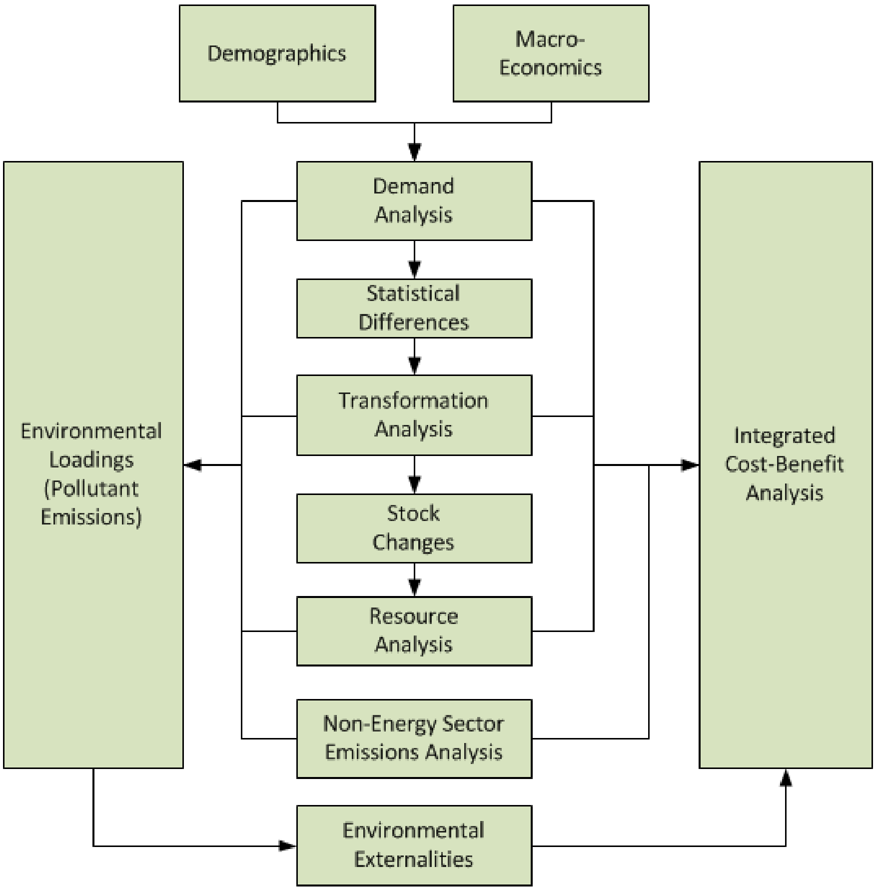


Figure 4-3 Structure of LEAP model [119]

4.2.1 The Analysis View

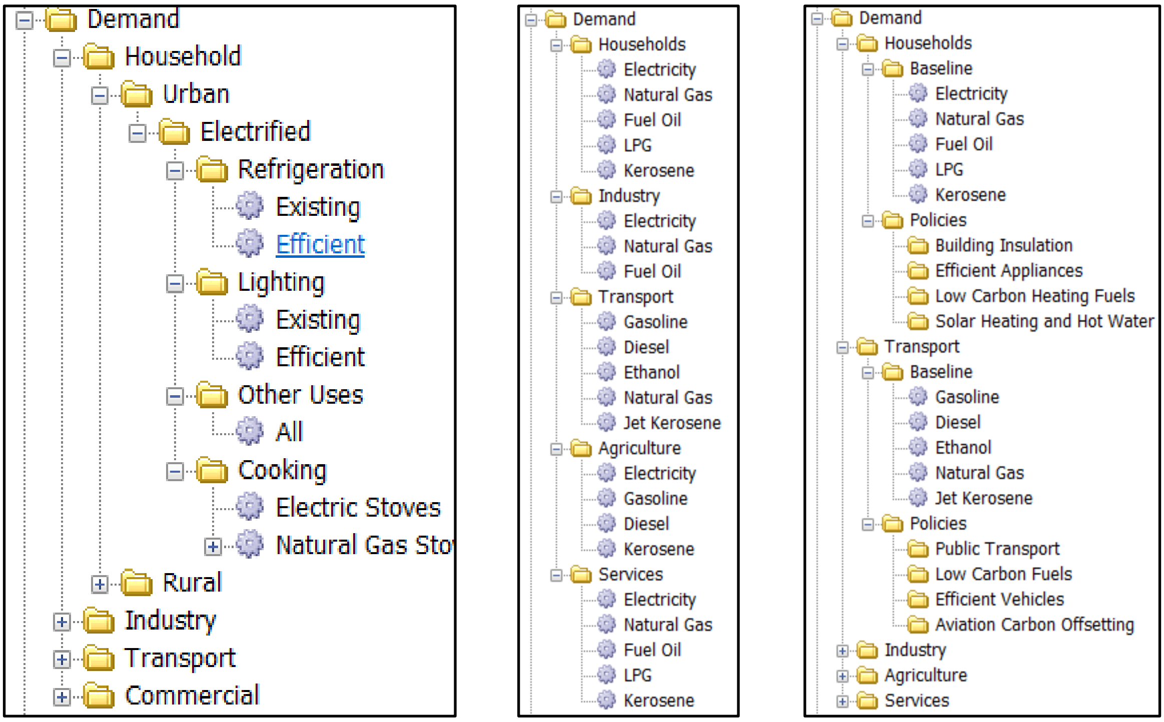
The analysis view is the design centre of the software. A section that is structured in the form a tree provides the platform for creating, organising and editing data. The data provides four main categories for the organisation of data in the model.

4.2.2 Key Assumptions

These are user defined variables which enable the creation of demographic (e.g. Population, rates of urbanization, household size), macroeconomic (e.g. GDP, interest rate) and other time-series variables (e.g. employment statistics, investment rate). Key assumptions are not calculated directly in LEAP but can be used in intermediate calculations. For example, population growth rate can be used to project domestic demand.

4.2.3 Demand:

Integrated energy analysis will normally begin with demand analysis, since all transformation and resource calculations rely on the demand requirement. LEAP provides flexibility on the organisation of demand and provides three approaches for modelling demand as illustrated in *Figure 4-4*.



a. Bottom-up b. Top-down c. Hybrid

Figure 4-4 Energy demand approaches in LEAP [119]

Bottom-Up or End-Use approach provides a detailed engineering based modelling account for sectors as well as end users and energy consuming devices. The Top-down or Econometric approach is an aggregation approach in which consumption is then divided into sections and fuels only. The Hybrid approach in LEAP makes use of the top-down approach for the reference scenarios, while the alternative scenarios are modelled as policy measures resulting in reduction of consumption over time [118]. Table 4-1 provides a summary of the pros and cons of the various approaches.

Table 4-1 Pros and Cons of LEAP demand modelling approaches [118]

Bottom-up	Top-down	Hybrid
Pros		
• Enables the assessment of impacts of changes due to policies. • Gives better understanding of energy usage.	• Less data intensive. • Forecast using simple historical trends. • Able to capture fiscal policies such as carbon tax	• Less data intensive than bottom-up. • Can capture technology base policies
Cons		
• Data intensive. • Hard to capture impacts of fiscal policies. • May require many trends and assumptions	Not well suited to examine technology based polices	Does not give insight on system structure in long term

4.2.4 Results View

The results view displays detailed results for all parts of the system including demand, transformation, resources, cost and environmental loading. The display view also contains tools for constructing variety of tables and charts which can be easily exported to word, excel or PowerPoint. Favourites features in the results view enables customised charts to be bookmarked for future reference.

4.2.5 Energy Balance View

The Energy Balance View displays energy summaries for any year of the model or calculated scenario as standard energy balance table, chart or shankey diagram. The shankey diagram that has replaced the diagram view available in older versions of LEAP provides superior visualisation as it shows the actual energy flow quantities.

4.2.6 Summaries View

This Summaries View can be used to create customized tables and graphical summary reports of results. The summary also contains the cost-benefits summary report which provides a summary of the cost and summary of the cost and benefit of the scenarios compared to chosen reference.

4.2.7 Technology Database (TED)

TED is a comprehensive quantitative data source on technology characteristics, cost and environmental impacts. TED includes data on approximately one thousand technologies, referencing reports by dozens of institutions including the IPCC, the U.S. Department of Energy, and the International Energy Agency (IEA), as well as by regional institutions that have developed data specific to energy technologies found in developing countries [119].

TED is particularly useful for calculating environmental loading of scenarios under consideration. The current version of LEAP (Version: 2015.0.30.0) contains global warming potential (GWP) values of all assessment reports by IPCC, which can easily be assessed on the effect screen. TED values can also be edited allowing for application of user defined emission factors. The TED is thus an important reference to researchers especially in developing countries such as Ghana where there is insufficient availability of data.

4.2.8 Notes View

The Notes View provides a word processing tool for entering documentation for each branch. Its interface is much like Word, enabling basic formatting to be done. The view, thus provide a means for referencing data and assumptions considered in the model [119].

4.2.9 Algorithm of the LEAP Model

The LEAP framework for calculating energy endogenous expansion, energy consumption, transformation (electricity generation, oil refinery), greenhouse gas emission and cost of production is presented in the following sections [119].

4.2.9.1 Endogenous addition

If a technology is specified to be added endogenously, LEAP calculates the capacity to add as follows:

$$C_{En}(MW) = D_p(PRM - RM) \qquad (4.\ 1)$$

Where C_{En} is the endogenous capacity addition required, *PRM* is planning reserve margin, *RM* is the reserve margin before addition and D_P is the peak requirement. *RM* and D_P are determined using equations (2) and (3) respectively.

$$RM(MW) = (C - D_p)/D_p \qquad (4.\ 2)$$

$$D_p = ED/LF \times 8760 \qquad (4.\ 3)$$

Where *ED* is the energy requirement and *LF* is the load factor (LF is either entered directly or calculated as average of load curve). *C* is capacity factor before addition, which is calculated as follows:

$$C = MA(C_{EnP} + C_{Ex}) \qquad (4.\ 4)$$

Where MA is the maximum availability of process, C_{EnP} is endogenous capacity added previously and C_{Ex} is the exogenous capacity.

4.2.9.2 Energy consumption

The total energy consumption is calculated as follows

$$TC(TWh) = \sum_{f}\sum_{t}\sum_{i} AL_{f,t,i} \cdot EI_{f,t,i} \quad (4.\ 5)$$

Where *TC* is the aggregate energy consumption of a given sector, *AL* is the activity level, *EI* is the energy intensity, *f* is the fuel type, *t* is the technology and *i* is the sector.

4.2.9.3 Greenhouse gas emission

The greenhouse gas emission (GHG) from final consumption is calculated as follows [106] :

$$GHG(MMtCO2e) = \sum_{t}^{n} fi_{g} \cdot P_{t} \quad (4.\ 6)$$

Where fi_g is the CO_2 emission factor during generation and P_t is the output power of technology

4.2.9.4 Cost

The total cost of a sector *(TC)* is calculated as follows

$$TC(US\$) = \sum_{t}^{n} Cc_{t} \cdot Ca_{t} + foc_{t} \cdot Ca_{t} + Vc_{t} \cdot P_{t} + Ce \cdot T_{GHG_{t}} \quad (4.\ 7)$$

Where *Cc* is capital cost of technologies, *Ca* is installed capacity of technology, *Vc* is variable operation and maintenance cost and *foc* is the fixed cost, *Ce* is the specified CO_2 externality cost and T_{GHG} is the total emissions.

4.2.9.5 Cost-benefit analysis

Cost-benefit analysis is an approach for estimating the strength and weaknesses of alternatives. It can also be described as an analytical tool that is used in determining options that provide the best in terms of savings in cost and other resources [120, 121].

The cost benefit analysis in LEAP is not intended to provide an analysis of the financial viability of options. Rather, helps identify range of socially acceptable policy options and provides a foundation for further financial analysis.

LEAP cost-benefit analysis calculates the cost of each part of the energy system including [119]:

- Capital cost of transformation system
- Operation and maintenance cost
- Cost of extracting primary resources
- Cost of imported fuels
- Benefits of exported fuels
- Externality cost of GHG emissions
- Other user defined cost such cost of efficiency programs.

LEAP provides flexibility in how cost-benefit analysis is conducted by providing an option for specifying cost boundary. Specifying a limited boundary can be very useful in modelling systems where data is only available for cost of fuels and not the cost of refining and mining [119]. A consistent boundary also prevents double counting of cost and benefits [121]

4.3 DEVELOPMENT OF GHANA LEAP MODEL

The Ghana LEAP model was designed with 2010 as the base year, to analyse the possible developmental structure of the generation system of Ghana up to 2040. The choice of this base year was due to availability of data. The national population census conducted by the Ghana Statistical Service [17] and a national energy survey by the Ghana Energy Commission [3], which were conducted in 2010, providing reliable data for the model. The selection of 2010 also provided opportunity to validate the results with real data for the past years (2010 to 2015). LEAP model requires data on several demographic, macroeconomic and other time series data as described in section 4.2.2. The key assumption variables and data considered in this thesis are discussed in this section.

4.3.1 Demographic Trends

The population of Ghana in 2010 was 24.7 million people, which was projected to be increasing at a growth rate of 2.4% [17]. This growth is similar to the 2.5% average for Sub-Saharan Africa but higher than the 1.6% of other lower-middle income countries [122]. Table 4-2 provides a summary of the demographic characteristics of the country in 2010.

Table 4-2 Demographic characteristics for 2010 [17]

Variable	Value
Population	24,658,845
Population growth	2.4%
Urban population	12,545,229 (50.9%)
Households	5,467,136
Urban households	3,049,438 (55.8%)

The electricity consumption pattern in Ghana varies significantly between urban and rural areas. In 2010, 83.8% of the urban households had access to electricity compared to only 39.5% of rural households. With the current urban population of 55.8% (2010), which is expected to increase to about 60% by 2040 [17], the energy demand for domestic consumption is expected to increase significantly by 2040.

4.3.2 Economic Characteristics

The Gross Domestic Product (GDP) average growth rate of Ghana from 2005 to 2009 was about 6% rising to a peak of 14% in 2011 because of the production of crude oil in commercial quantities, which began in late 2010. Table 4-3 shows the GDP of Ghana at constant 2006 prices from 2010 to 2015 [123].

Table 4-3 GDP of Ghana at constant 2006 prices [123]

	2010	2011	2012	2013	2014	2015
GDP (Million US$)	16848	18158	16615	16790	11402	9221
GDP Growth rate (%)	7.9	14	9.3	7.3	4	3.9

It is observed from Table 4-3 that the GDP growth dropped to 4% in 2014 after the peak of 15% in 2011. This is mainly due to the load shedding that was experienced for much of 2014 and 2015 because of insufficient generation. Damage to the West African Gas Pipeline resulted in a shutdown of the pipeline for maintenance cutting out supply to the gas turbines.

Even though agriculture sector serves as the main source of employment especially in the rural areas, the service sector is the backbone of the economy accounting for 51.1% of GDP in 2010. The trend of GDP share for the various sectors of the economy of Ghana is illustrated in Table 4-4.

Table 4-4 Distribution of GDP at basic economic activity (%)[123].

	2010	2011	2012	2013	2014	2015
Agriculture	29.8	25.3	22.9	22.4	21.5	20.3
Industry	19.1	25.6	28	27.8	26.6	25.3
Mining	2.3	8.4	9.5	9.4	8.0	6.3
Manufacturing	6.8	6.9	5.8	5.3	4.9	4.8
Oil and gas	0.4	6.7	7.7	8.2	7.2	5.8
Construction	8.5	8.9	11.5	12	12.7	13.2
services	51.1	49.1	49.1	49.8	51.9	54.4

The most energy intensive sectors of the economy include the mining and manufacturing sectors. Growth in these sectors will therefore lead to significant increase in demand for electrical energy. For Ghana to benefit from its oil industry there is clearly a need to expand its electrical generation sector.

To model the industrial demand, the GDP elasticity of demand of 1.0 was assumed. This means a 1% increase in GDP yields a 1% increase in energy demand. This is to conform to the official projections presented in the strategic national plan [4]. The GDP growth rate of 8% was adopted for Base Case Load Projection from 2010 to 2020, increasing to 12% from 2020 to 2040 when the power supply is expected to improve [4].

4.3.3 Energy Demand: Past and forecast

4.3.3.1 Past demand

The demand for electricity in Ghana has been growing at a rate of 9.7% per annum in the past 10 years while the corresponding system peak demand has also been growing at 5.6% per annum as sown in Table 4-5.

Table 4-5 Historical demand and Generation

Year	Demand		Peak		Generation	
	GWh	% growth	MW	% growth	GWh	% growth
2005	6935	19.7	1325	26.3	6788	12.4
2006	7838	13	1393	5.1	8430	24.2
2007	6822	-12	1274	-8.5	6978	-17.2
2008	8043	17.9	1367	7.3	8324	19.3
2009	8385	4.2	1543	12.9	8958	7.6
2010	9232	10.1	1506	-2.4	10167	13.5
2011	10565	14.4	1665	10.6	11200	10.2
2012	11620	10	1729	3.8	12024	7.4
2013	12127	4.4	1943	12.4	12870	7
2014	13678	12.8	2061	6.1	12963	0.7
Last 5 years		9.6		7.3		5.5
Last 10 years		9.7		5.6		9

However the peak demand growth rate has increased to 7.3% during the past 5 years while demand within the same period has remaind fairly constant at 9.6%.

Generation in 2014 was 12,963 GWh which is almost twice the value 10 years ago. It is also observed that the generation growth rate during the past 5 years is almost half that of demand. This means the generation capacity growth is lagging behind demand which will lead to insufficient generation if steps are not taken to addreess this trend. The maximum demand recorded in year 2014 was 2061 MW but it was 1506 MW in 2010 and 1325 MW ten years ago.

4.3.3.2 Future demand

A good demand forecast is essential for proper long term generation planning. This is because a good generation system should be able to meet the required demand, which is the focus of every long-term generation planning studies. Various techniques have been employed for aggregate load forecasting in Ghana. Adom & Bekoe [7] compared the Autoregressive Distributed Lag Model (ARDL) and partial adjustment model (PAM) for modelling the aggregate demand of Ghana from 2000 to 2020 and projected a demand average growth rate of 12%. Their projections are closely related to the historical demand growth rate and that of Abledu [6] who appplied ARIMA (Autoregressive integrated moving average) models to forecast the aggregate demands of Ghana. A forecast demand rate of 7 to 9% was also projected depending on the econmic growth rate in the official projections by Ghana grid company [124].

The Bottom-Up demand model approach in LEAP was adopted for modelling the future energy demand in this thesis. Figure 4-5 shows the LEAP demand model of Ghana showing the various demand sectors.

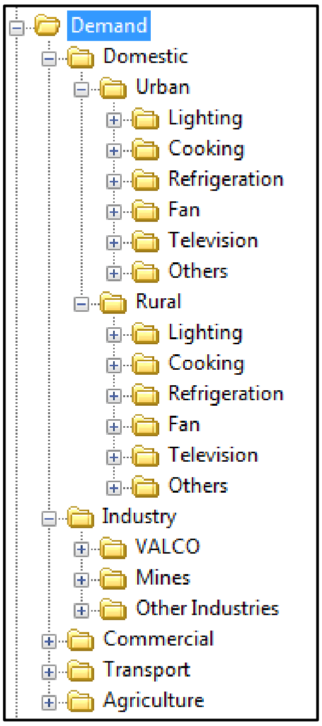


Figure 4-5 LEAP demand forecast model of Ghana

The energy intensity data used for the model was developed from an energy consumption survey (Appendix B) conducted by the Energy Commission in 2010 [3]. The results of the energy demand projection from 2010 to 2040 using LEAP energy demand model is presented in Figure 4-5.

The results of the energy demand projection for Ghana from 2010 to 2040 using LEAP energy demand model is presented in Figure 4-6. The results show that demand projection will increase into the future with average growth rates of 9%, 8% and 8% within the periods of 2010–2020, 2020–2030 and 2030–2040 respectively. These growth rates follow the historical demand growth of the country, and are consistent with official load projections [124].

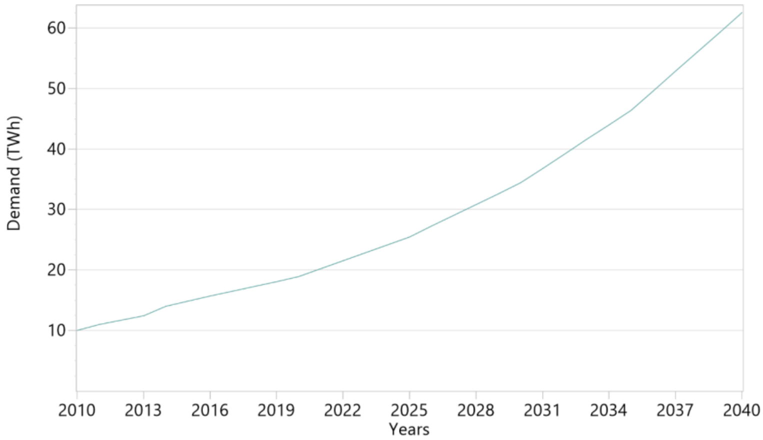


Figure 4-6 Electricity demand forecast for Ghana

The total energy requirement of Ghana by 2020 will be 18.88 TWh increasing to 62.5 TWh at the end of the study period. This means that the current installed capacity of 2.19 GW should be expanded to 5.0 GW and 16 GW in 2020 and 2040 respectively, if the country is to be able to meet its future electricity requirement. This therefore requires the exploration of all energy sources available in the country to meet future generation requirements.

It is important to note that the actual demand may be higher than the projection in this thesis. This is because the projections are based on historical demand and GDP values which themselves may not reflect the actual demand. The insufficient generation and low electrification rate especially in rural areas lead to suppressed demand. Thus, the historical trends alone may not fully capture the real demand, which is best captured by back casting [125]. This is confirmed by the trend in historical demand data of Ghana (Table 4-5), which shows a negative demand growth during the energy crises in 2007. This clearly shows that the official demand projection is closely related to generating capacity.

The focus of the thesis is to explore possible pathways for sustainable power generation in Ghana and to undertake an environmental and economic analysis of the various scenarios. Thus, this demand will be used for all the scenarios.

4.3.3.3 Validation of the demand model

In this section, the Ghana LEAP demand model results developed in this study was tested with real data from 2010 to 2015 and official load projections. The details of the comparison is presented in Table 4-6. The first part of Table 4-6 compares the LEAP results with real data while the second part compares the model results with the official projections.

Table 4-6 Validation of LEAP demand model

Real data verses LEAP					
Year	**2010**	**2011**	**2012**	**2013**	**2014**
Real (TWh)	9.23	10.57	11.62	12.13	13.97
LEAP (TWh)	9.91	11.01	11.69	12.40	13.17
Error (%)	7	4.2	0.6	2.3	-5.8
GRIDCO verses LEAP					
Year	**2015**	**2018**	**2020**	**2023**	**2026**
GRIDCO (TWh)	13.93	16.30	18.15	21.39	25.29
LEAP TWh)	13.98	16.73	18.88	22.58	27.04
Error (%)	0.3	2.66	0.4	5.6	6.9

Two main official load projections have been undertaken for Ghana's aggregate load demand: Ghana's Energy Commission projection [4] from 2006 to 2020 and the updated projection by GRIDCO [124] from 2012 to 2026. Both projections were undertaken based on 3 growth scenarios as shown in Appendix C. GRIDCO forecast being the most recent was adopted for validating the Ghana LEAP Demand model developed in this thesis. This is because it made use of much latest trends in energy demand. A careful analysis of the results of the three demand projections by GRIDCO and Real data from 2012 to 2014 suggest that their base case projection values best represents the current trend in demand and was selected for validating the results of the LEAP model.

The differences between the LEAP projections and the real data are moderate. In all the cases except that of 2014, the LEAP projections are slightly higher than the official projection with the highest error of 7% occurring in the base year. It was therefore concluded that the largest error in demand projection that will be obtained in this thesis would be approximately 7%. Based on the comparison results presented in Table 4-6, it was concluded that the Ghana LEAP demand model is capable of accurately modelling the future demand trends of Ghana. The slight differences are largely due to the various assumptions made. These differences were considered insignificant and illustrate the adequacy of the model. It was observed that a more accurate input operating characteristic such as site-specific data for each plant would further reduce these errors.

4.3.4 Development of LEAP Transformation Models for Base year (2010)

4.3.4.1 Technology cost data

The main source of electricity in Ghana has been from hydropower. However, recent expansion in the generation sector has resulted in significant expansion in thermal generation. The review of energy resources in Ghana shows clearly that Ghana is endowed with high potential for generation of power from renewable power resources as shown in Chapter 2. To perform an analysis of the possible generation expansion plans, LEAP required the technological data as well as the technical specifications of the different generation systems. The current investment as well as operational and maintenance cost of selected technologies were obtained from literature review of some of the most reliable current studies (Table 4-7).

Table 4-7 Cost of selected technologies for base year

Technology	Cost	Unit	NREL	WEO 2014 (2012 US$)	ETP 2014	Greenpeace
Thermal CC	Capital	$/kW	1230	700	1000	
	Fixed O&M	$/kW-Yr	6.31	25		
	Variable O&M	$/MWh	3.67			
Large Hydro	capital	$/kW	3500	1870		3160
	Fixed O&M	$/kW-Yr	15	45		74
	Variable O&M	$/MWh	6			
Small Hydro	Capital	$/kW		2990		
	Fixed O&M	$/kW-Yr		60		
	Variable O&M	$/MWh				
PV	Capital	$/kW	2830	2590	4000	2350
	Fixed O&M	$/kW-Yr	50	26	40	24
	Variable O&M	$/MWh	0			
Wind onshore	Capital	$/kW	1980	2213	1800	1791
	Fixed O&M	$/kW-Yr	60	39.55	36	46
	Variable O&M	$/MWh	0	0		
Biomass	Capital	$/kW	3830	2160		2380
	Fixed O&M	$/kW-Yr	95	76		83
	Variable O&M	$/MWh	15			
MSW	Capital	$/kW		7320		
	Fixed O&M	$/kW-Yr		278		
	Variable O&M	$/MWh				
Ocean Tidal	Capital	$/kW	5880			7090
	Fixed O&M	$/kW-Yr	198			204
	Variable O&M	$/MWh				
Coal	Capital	$/kW	2890	2300		
	Fixed O&M	$/kW-Yr	23	92		
	Variable O&M	$/MWh	3.71			

Source: [51, 53, 126]

It is observed from table 4-7, that the different studies used different cost assumptions for the technologies considered. This is because technology costs are site specific and varies significantly depending on the location. To this end, actual and recent official estimated cost of generation plants in Ghana [124] were reviewed and compared to the international estimates. Table 4-8 gives a summary of the official investment cost of various plants in Ghana.

Table 4-8 Cost of technologies in Ghana

Plant	Capacity (MW)	Investment cost ($/KW)	Status
Bui Hydro	400	1555	Completed in 2013
Juale Hydro	87	3551	Estimated cost
Pwalugu Hydro	48	3625	Estimated cost
Hermang hydro	93	2688	Estimated cost
Kulpawn	36	8111	Estimated cost
Daboya	43	4698	Estimated cost
Combined cycle (NG)	300	1067 - 1333	Estimated cost
Coal Plant	250	2160 - 2512	Estimated cost
Navrongo PV	2.5	3240	Completed 2013
TIDAL wave	1000	4000	Under construction
Biomass	40 - 100	3240 - 3400	Estimated cost
Wind	50	1380 - 1620	Estimated cost

Source: [124, 127]

The future year's investment cost of the conventional energy systems in Ghana (large Hydropower and thermal power) were assumed constant throughout the study period while that of renewable systems were assumed to decrease per projections presented in [51]. in this thesis.

Table 4-9 shows the investment, fixed Operational and Maintenance (O&M) and variable O&M values considered in the LEAP model for the various time intervals considered in the study. Fixed O&M is the part of the maintenance cost of a plant which does not depend on the operation of the plant. Components of fixed O&M include property tax and insurance, planned and unplanned maintenance, administration, operation staff as well as re-investments within the scheduled lifetime of the plant. Variable O&M generally refers to consumption of auxiliary material such as fuel additives, lubricants and treatment and disposal of waste. Renewable energy systems such as Wind and PV have very low variable O&M, which was considered zero in this thesis.

Table 4-9 Cost data considered in LEAP

Technology	Investment Cost ($/kWh)		Fixed O&M ($/kW-Yr)		Variable O&M ($/MWh)	
	2010	2040	2010	2040	2010	2040
Large Hydro	1600	1600	7	7	2.72	2.72
Small Hydro	3300	3300	15	15	6	6
Thermal (NG)	1200	1200	6.31	6.31	3.67	3.67
PV	3200	2010	50	37	0	0
Onshore Wind	1620	1620	49	49	0	0
Tidal wave	4000	3420	147	112		
Biomass	3300	3300	83	83	13	13
MSW	7320	6000	278	223	28	23
Coal	2300	2300	23	23	3.71	3.71

The Operation and Maintenance cost were calculated using the percentage rates from National Renewable Energy Laboratory (NREL) cost and performance data for power generation technologies rates [126].

4.3.4.2 Cost of fuel

The prices of fossil fuel resource are particularly difficult to predict because of its high price fluctuations in the world market. However, the bench mark fuel price projections in IEA annual energy outlook 2015 [128] were considered as the most reliable assumptions and hence adopted for this thesis (Table 4-10). These prices are the average spot (Henry hub) price in the United States and hence did not include local port as well as transportation charges.

Table 4-10 Average price projections in United States

Fuel	2020	2025	2030	2035	2040
Crude oil ($/bbl)	90	112	142	180	229
Natural gas ($/MMBtu)	5.54	6.72	7.63	9.70	12.73
Coal ($/MMBtu)	2.14	2.48	2.92	3.41	3.96

Source: adapted from: [128]

Even though Ghana started producing oil and gas in commercial quantities in 2010, the prices in the local market are determined by the international prices and are adjusted in line with fluctuations in the international market. For example, the price of locally produced natural gas $8.75/MMBtu (million British Thermal Units), made available for power generation in 2014 was higher than that of imported gas, $8.84/MMBTU, through the West Africa gas pipeline supply from Nigeria [3]. A similar trend is observed in 2015 where the locally produced gas was $8.84/MMBtu compared to WAGP average price of $8.75/MMBtu [129]. The breakdown of the WAGP gas price for VRA thermal generating plants in 2014 and 2015 is presented in Table 4-11, while that of the locally produced gas from Jubilee-Atuabo fields is presented in Table 4-12.

Table 4-11 WAGP gas pricing components for VRA in 2015 [129]

	Price ($/MMbtu)		
Details	**2014**	**Jan-Jun 2015**	**Jul-Dec 2015**
Gas Purchase	2.2.4688-2.4776	2.2901	1.6171
ELPS Transport	1.2745	1.2959	1.2959
WAGP transport	4.3465	5.0265	5.0265
WAGP credit support charge	0.1299	0.1299	0.1299
WAGPA charge	0.0600	0.0600	0.0600
Pipeline protection zone charge	0.0300	0.0250	0.0250
Shipper fee	0.1000	0.1000	0.1000
Fuel charge	0.0749-0.0750	0.0717	0.0583
Delivered Gas price[3]	**8.3708-8.3798**	**8.9991**	**8.3127**

Source: Adapted from [129]

Table 4-12 Jubilee-Atuabo gas pricing component in 2015 [129]

Component	**Price ($/MMBtu)**
Gas commodity price	2.9
Gathering, Processing	5.28

[3] Delivered gas price is not an absolute sum usually is total less the repetitive charges

and transportation	
PURC levy	0.66
Delivered Gas price	**8.84**

It is evident from Table 4-11 and Table 4-12 that price difference is largely due to the high cost of processing and transportation of the locally produced gas. However, it is worth noting that the gas commodity price (the cost at the pump) of the gas produced in Ghana is slightly higher than that of Nigeria.

The international price of Natural Gas (NG) varies depending on the market. The natural gas prices in the North Sea/Europe are significantly higher than the Henry hub/United States as shown in Table 4-13. Table 4-13 further shows that the WAGP gas price made available for power generation in Ghana is about twice that of the price in the North Sea/Europe.

Table 4-13 Average Natural gas and crude oil prices from 2010 to 2015 [129]

	Natural Gas ($/MMBtu)					
Source	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
WAGP		6.56	8.19	8.38	8.49	8.80
Henry Hub/USA		3.59	2.75	3.71	4.52	3.88
North Sea/ Europe		8.70	8.90	10.72	10.05	7
		Crude oil ($/bbl)				
Ghana[4]	80	111	113	109	99	52(60[5])
Gulf Coast/USA	79.4	94.9	93.3	97.9	93.3	48.7
North Sea/UK	70	111	112	109	99	52

The average price for crude oil (oil) sourced by Ghana in 2014 was $ 99 /bbl which dropped to $52 /bbl in 2015. However, the price of crude oil for power generation in 2015 was 15% more than the delivered price [129]

[4] Price excludes transportation and other charges
[5] Price for power generation

To model the feedstock fuel of the thermal plants considered in the Ghana LEAP model, the actual LCO (light crude oil) and natural gas prices made available for power generation in Ghana were used for the reference years, that is, from 2010 to 2015. For the future years, the price projections in [128] were adopted. Transportation and taxes were calculated using 20% and 90% for crude oil and natural gas respectively to reflect the current price trend [129]. Table 4-14 shows the fuel prices used in the LEAP model.

Table 4-14 Fuel prices used in the model

Fuel	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
Crude oil ($/bbl)	92	128	130	125	114	60	103	129	163	207	263
NG ($/MMBtu)		6.56	8.19	8.38	8.49	8.80	10.5	12.8	14.5	18.4	24.2
Coal ($/MMBtu)	-	-	-	-	-	3.17	3.42	4	4.67	5.46	6.34

Ghana has no known coal reserves. The model therefore assumed that all coal will be imported. The coal price projections were therefore based on the projections, while transportation, taxes and processing charges were assumed to be 60%.

4.3.4.3 Modelling the generation system of Ghana in LEAP

The dependent installed capacity of Ghana in 2010 was 1865 MW consisting of two large hydro dams with capacity of 1040 MW with the remaining contribution from six thermal power plants [130]. To model the generation system of Ghana in LEAP, the various generating plants were aggregated. This means that single hydro and thermal plants were modelled to represent the system.

The operational characteristics of the plants used in modelling the generation system from 2010 to 2014 are presented in Table 4-15.

Table 4-15 Operational characteristics of generation plants in Ghana

	Dependable installed capacity(MW)					
Plants	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Hydro	1040	1040	1040	1420	1420	1420
Thermal	765	765	875	1130	1130	1376
PV				2	2	2
	Average availability (%)					
Hydro	76.78	83	88.6	66.2	67.4	47
Thermal	46.77	46.77	47.45	46.8	46.8	46.7
PV				20	20	20

The data in Table 4-15 was developed from actual plant operational data obtained from energy outlook of Ghana from 2011 to 2015 [3, 129]. (Detailed plant operational characteristics are available in Appendix D). All the plants were modelled as combined cycle plants because plans are far advanced to convert all the remaining simple cycle plants into combined cycle [4].

Most of the thermal plants in Ghana are designed to operate on LCO and natural gas. Natural gas is the preferred fuel when available because of its relatively low cost and lower environmental impact. However, because of insufficient supply, LCO continues to contribute almost half of the feed stock fuel [3]. The feedstock ratio of 55% NG and 45% LCO was assumed for 2010 to 2014. Beyond 2014, the ratio was interpolated to 80% and 20% for natural gas and LCO respectively by 2020, and eventually to 100% natural gas by 2030. This is in line with the proposals to operate the thermal plants fully on natural gas described in the Strategic National Energy plan of Ghana [4].

4.3.5 Generation Model Validation

To ascertain the viability of the Ghana LEAP model, the 2010 generating system of Ghana was modelled and compared with official values from [130]. The results of the comparison are presented in Table 4-16.

Table 4-16 Official data and LEAP results of Ghana's power system for 2010

Plant	Generation (GWh)		
	Official	**LEAP**	**Error (%)**
Hydro	6994.84	6995	0.0
Thermal	3134	3134	0.0
2010	**10128.84**	**10129**	**0.0**

The model produced excellent generation results, which closely matched the recorded data as shown in Table 4-16. Comparing the results of the official data and the LEAP model, it was found that the Hydro generation by the LEAP model was slightly higher than the official value with an simulation error of 0.0%, while that of thermal generation were exactly the same. The high correlation between the official data and LEAP generation is interesting because the power plants were aggregated according feedstock fuel. The results however, may be explained by the fact that, actual operation characteristics and availability were employed in the LEAP model.

To ascertain the accuracy of the LEAP model, the generation results from the model were compared with official data from 2011 to 2014 as shown in Table 4-17.

Table 4-17 Official data and LEAP generation from 2011 to 2014

Year	Generation (GWh)								
	Hydro			**Thermal**			**PV**		
	Official	**LEAP**	**Error (%)**	**Official**	**LEAP**	**Error (%)**	**Official**	**LEAP**	**Error (%)**
2011	7561	7562	0.01	3134	3134.24	0.01	-	-	-
2012	8071	8071.81	0.01	3639	3637	-0.06	-	-	-
2013	8233	8234.75	0.02	4635	4632.69	-0.05	4	4.38	9.5
2014	8387	8384.75	-0.03	4635	4632.64	0.05	4	4.38	9.5

The results in Table 4-17 show high correlation between the official data and LEAP generation for the Hydro and thermal plants for all the years under consideration with highest error of -0.06% and -0.03% for thermal and hydro generation respectively. This means that the largest error in hydro and thermal generation that will be obtained in the thesis will be 0.03% and 0.06% respectively. Surprisingly, the simulation error for the PV plant was rather 9.8%, which was significantly higher than the errors observed for the hydro and thermal plants. A possible explanation for the slight difference between the LEAP model PV generation and the official data may be partly due to the assumptions made because of unavailability of real operating data of the PV plant, which started operation in 2013. Considering the assumptions made, however, these errors were considered insignificant and illustrate the adequacy of Ghana LEAP generation model developed in this thesis.

4.4 SUMMARY

An overview of the applied methodology is presented in this chapter. The chapter is divided into three sections: the first section described the adapted scenario framework. It provided a comprehensive description of the five main steps of the improved methodology. The section provided a theoretical background of the LEAP model including its structure and algorithms. The last section described the modelling of the generation system of Ghana using LEAP. The section also presents the key assumptions and data applied in the model. Finally, the results of the developed Ghana LEAP for the past years, 2010 – 2014 were validated using measured data.

CHAPTER 5

ANALYSIS OF THE GENERATION EXPANSION PLAN OF GHANA

5.1 SCENARIO DESCRIPTION

The scenarios developed for this study fall under four main classes: reference expansion plan (Base case), Plan with coal (Coal); expansion plan with implementation of various renewable energy policies and strategies (Modest RET and High RET scenarios) and optimum scenario developed by LEAP. This chapter discusses the reference and the RET scenarios. The optimum scenario is captured in Chapter 6.

5.1.1 Base Case Scenario

The Base Case scenario (reference scenario) is based on the government of Ghana's planned expansion of electricity capacity and proposed mitigation options. Much of the formulation of the base case is available in the Strategic National Energy Plan [4]. The current generation capacity addition in Ghana shows an increasing expansion in thermal power generation that operates largely on natural gas (NG) and crude oil (oil). This expansion trend was assumed to continue in the Base Case Scenario with the addition of renewable power systems based on the Generation Master plan of Ghana [124]. The scenario also took into consideration committed systems that either are currently under construction or have been granted permits by Energy Commission of Ghana [131]. The system was modelled to allow LEAP to endogenously add any additional thermal plants in units of 300 MW to meet the growing demand as well as the Specified Reserve Margin. The reserve margin was interpolated to increase from 18% in the base year (2010), to 20% in 2040. The reserve margin reflects the reliability of the generation system. It is the difference between the effective installed capacity and system peak load expressed as a percentage [56]. Ghana has been operating at negative reserve margin in the past five years due insufficient capacity addition, inadequate fuel supply, coupled with increasing demand [3]. GRIDCO has however established a stability criteria including an 18% reserve margin [132]. As such, for this analysis, a minimum reserve margin of 18% was adopted.

The main characteristics of the base case scenarios are summarised as follows:

- No restriction on the use of fossil fuel for power generation
- No CO_2 emission reduction targets
- The expansion will be mainly due to construction of combined cycle thermal plants.
- The current single cycle plants will be upgraded to combined cycle plants
- Natural gas will be the main fuel for the thermal plants when available.
- Non-conventional Renewable Energy Technologies (NRET) will be expanded to generate about 10% of the total generation by 2030. NRET in this context does not include large hydro generation.

5.1.2 Coal Scenario

Coal scenario is designed with the same expansion trend as that of the base case scenario, except with the introduction of coal plants to take a share of new natural gas thermal plants. This scenario assumes the introduction of coal plants to meet 10% of new thermal plants share. The scenario assumes the construction of coal plants from 2016 onwards.

5.1.3 Modest RET Scenario

Modest RET scenario focuses on the promotion of renewable energy technologies which have significant potential. Thus, PV, Wind, small Hydro, wave, biomass and MSW are integrated in moderate amounts with the aim of increasing the renewable capacity[6] to about 20% by year 2030.

5.1.4 High RET Scenario

High RET Scenario explores the full potential of RET. Thus, emphasis is placed on deploying renewable energy technologies based on confirmed domestic potential. This scenario assumes shifting of policy towards the high development of low emission technologies with reduction in fossil fuel generation.

5.2 RESULTS AND DISCUSSION

5.2.1 Technical Results

The generation outlook of Ghana under various policy directions described in the scenarios is presented in Figure 5-1. It is observed from Figure 5-1 that the installed capacity of Ghana will need to be expanded to at least 16 GW in order to meet demand and the specified reserved margin.

[6] Renewable energy in this case does not include Large hydro generation

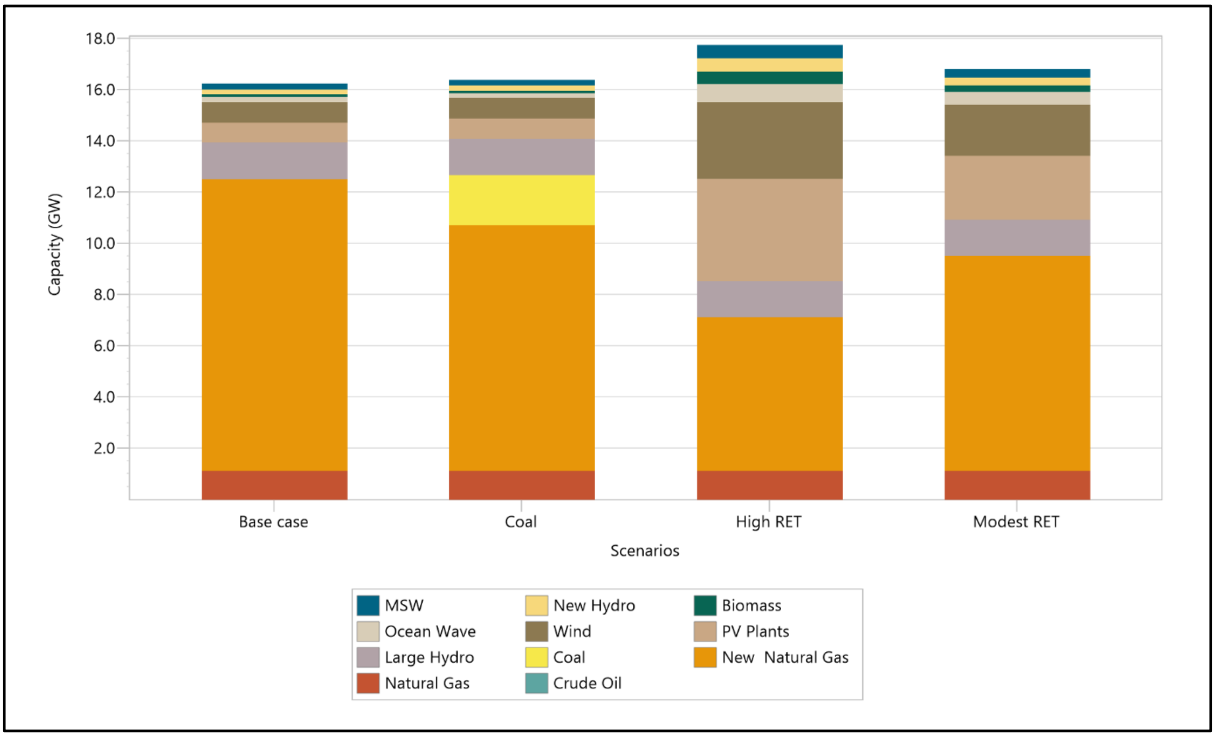


Figure 5-1 Installed capacities of scenarios at the end of study period (2040)

Higher installed capacities will be required for the Renewable Energy Technologies (RET) scenarios. This is due to the relatively low capacity credit of renewables considered in higher capacities in RET scenarios and conforms to the finding of McPherson and Karney [58], which suggest that higher capacities of RET need to be constructed to be able to meet the same demand as that of the thermal plants. The higher RET deployment will ensure higher diversity of the generation mix with a reduction of the thermal share of generation. This will result in 57% and 38% renewable share for high and modest RET scenarios respectively compared to only 18% for the base case.

5.2.1.1 Technical results of Base case scenario

The results of the generation expansion of the system in the base case scenario is presented in Figure 5-2. The system capacity increased from 2552.50 MW in 2014 to 4122.50 MW in 2016 to meet the total demand of the country. This is because the 2014 capacity was not adequate in meeting the country's demand as explained in Chapter 2. This scenario was however modelled to allow LEAP to endogenously add new NG plants in units of 300 MW to meet the total demand including VALCO working at full capacity, as well as the reserve margin from 2015 to 2040. The model assumed adequate availability of fuel throughout the planning period. The existing thermal plants were switched to operate fully on NG from 2030 onwards to conform to the current policy direction [4].

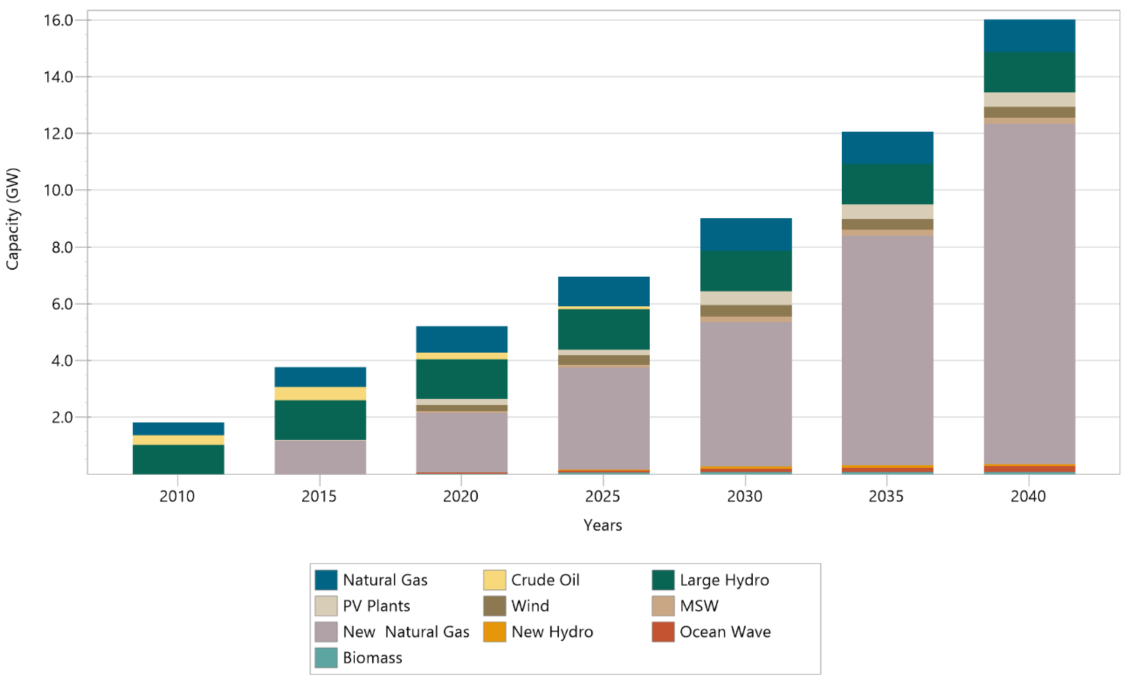


Figure 5-2 Electricity generation capacity by plant type for base case

It is evident from Figure 5-2. that the current installed capacity will have to be expanded to about 16 GW and increased to over 300% from the 2015 capacity, if the country is to meet its generation requirement by 2040 based on the current trend in demand. The capacity results further show a significant reduction in the capacity share of hydro plants. The share of hydro capacity decreased from 57.6% in 2010 to 20% and 9% in 2020 and 2040 respectively. This is because of the near exhaustion of the hydro energy potential resulting in high penetration of thermal generation. The exogenous expansion of the NRET into the generation system have resulted in an increase in their share from the base year level of 0.1% to about 12% in 2020, and remaining almost the same share till the end of the study period.

In the base year, 13 TWh of electricity was generated with hydro accounting for 64.4% of the generation and solar accounting for only 0.1%. The rest was from thermal plants that operated on NG and light crude oil. The projected generation by the model in the base case shows a slight increase in hydro generation with the introduction of tidal wave generation and small hydro systems in 2018 and 2019 respectively. The model predicted a switch from hydro dominated generation to NG thermal by 2040 as illustrated in Figure 5-3, while the relative percentage share of generation by source is presented in Figure 5-4.

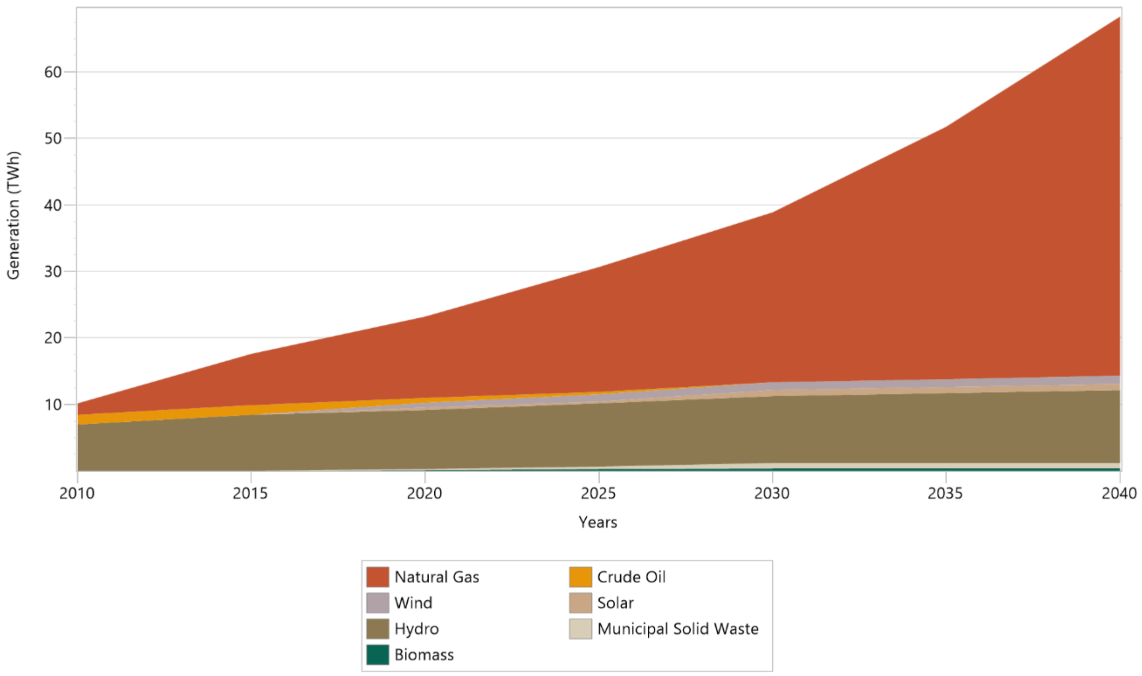


Figure 5-3 Electricity generation by source in base case

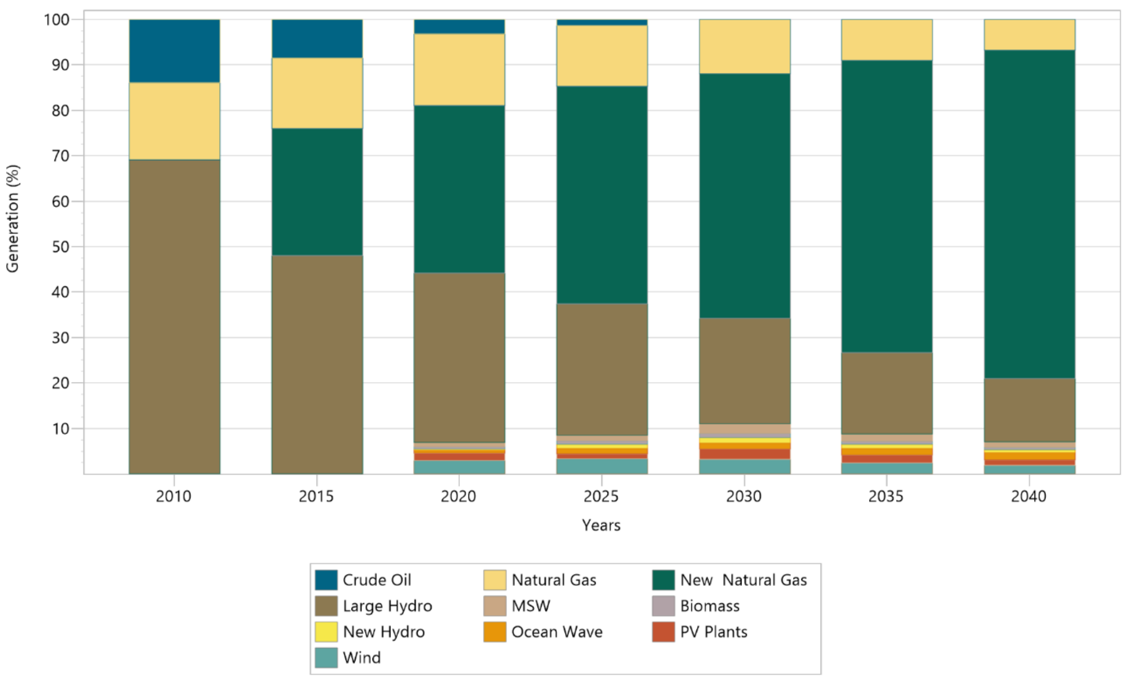


Figure 5-4 Percentage share of generation by source in base case scenario

It is observed from Figure 5-4 that thermal generation largely from NG becomes the dominant generation system of the country accounting for 54% of the generation in 2020, rising to 65% and 79% in 2030 and 2040 respectively, to meet the increasing demand. The expansion schedule of the base case scenario has thus resulted in the reduction of renewable share of generation to 21% of the total generation by the end of the study period. This is made up of the 14% from the conventional large hydro plants and the rest from the NRET technologies.

Figure 5-4 further highlights the contribution of NRET to the generation requirements of the base case scenario. NRET technologies generation share in the base case scenario increased from less than 0.1% in 2013 to more than 10% in 2030 to conform to the revised official renewable target of Ghana [133]. NRET share is dominated by wind generation, which contributes 3% and 2% of the total generation in 2020 and 2040 respectively. The scenario considered higher penetration of PV plants compared to other NRET, however the lower availability of PV plants limits their output

5.2.1.2 Technical results of Coal scenario

The planned generation with coal scenario considered the introduction of coal generation plants as government of Ghana policy changes towards shifting future thermal investment towards coal. The exogenous capacity expansion of this scenario is the same as that of the base case scenario. The planned generation with coal scenario was modelled to endogenously add both coal and NG thermal plants to meet future demand and reserve margin, with coal plants only taking a percentage of the NG generation.

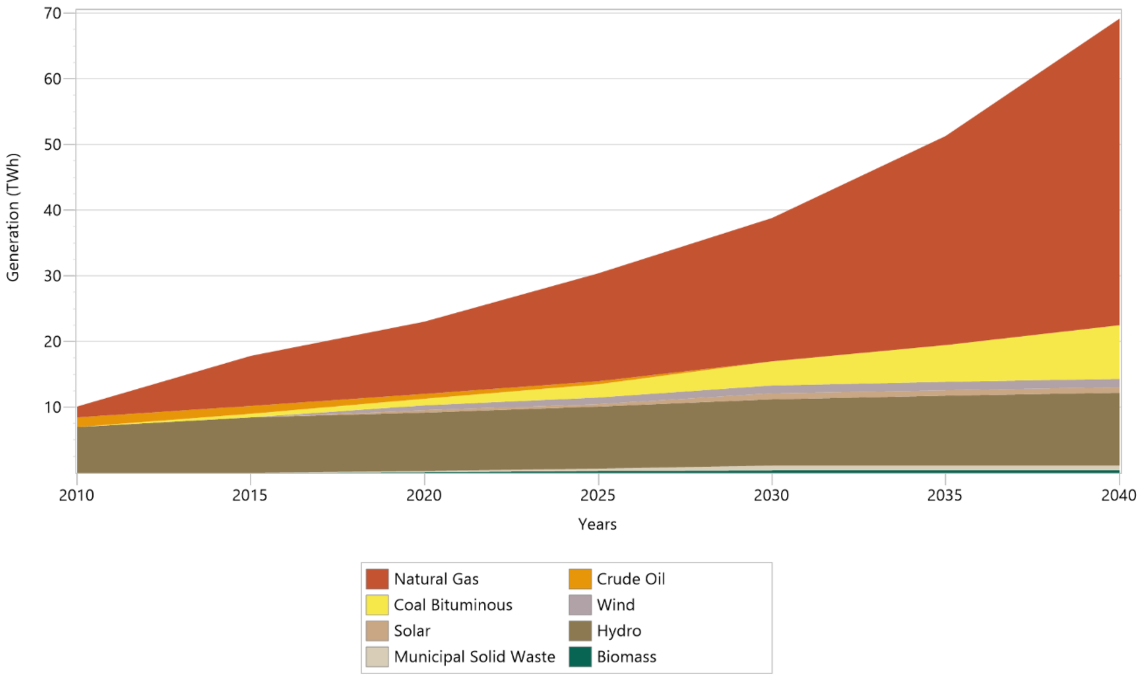


Figure 5-5 Electricity generation by source in coal scenario

Figure 5-5 shows that the total generation remains the same as that of the reference scenario,

5.2.1.3 Technical results of Modest RET scenario

This scenario examines the effect of conservatively adding NRET technologies into the national energy mix. The moderate introduction of NRET technologies saw a gradual reduction in the share of thermal generation compared to the base case in Figure 5-6. However, thermal generation continue to dominate as more NG thermal plants were endogenously added to meet the growing demand as the NRET reach their maximum capacity as stipulated in the scenario description.

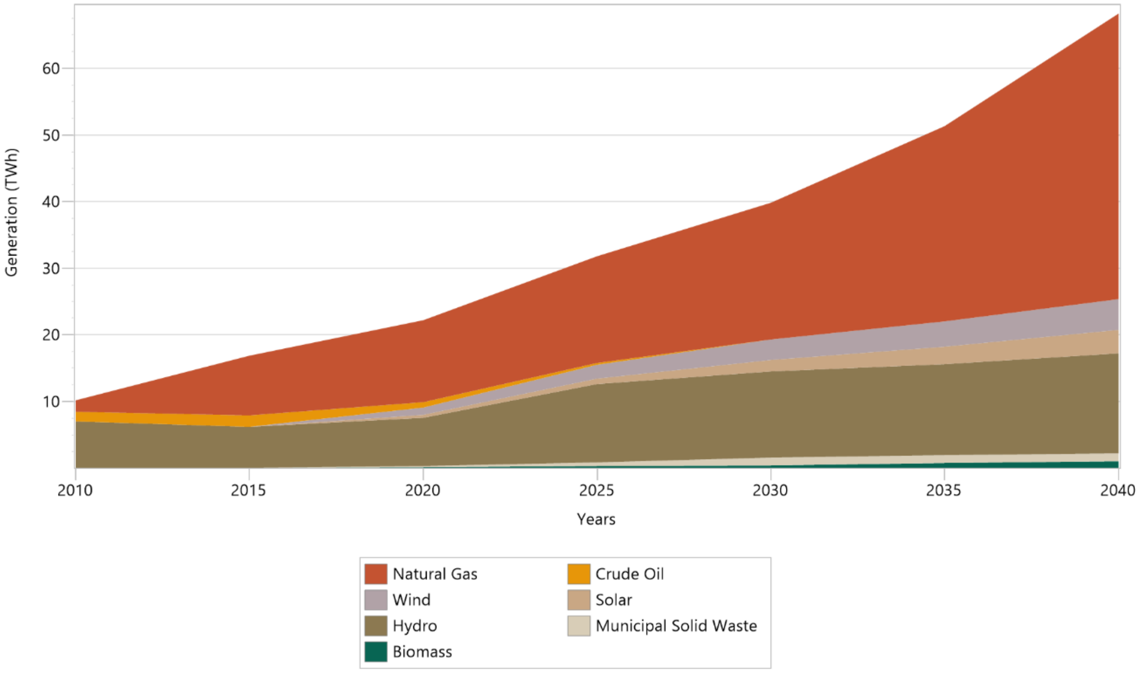


Figure 5-6 Generation by plant type for modest RET scenario

The share of renewable generation doubled in the modest RET scenario compared to the reference scenario with NRET contributing 17% of the total generation by 2020, increasing marginally to 21% at the end of the study period. The percentage contribution to generation by plant type in the moderate renewable scenario is presented in Figure 5-7.

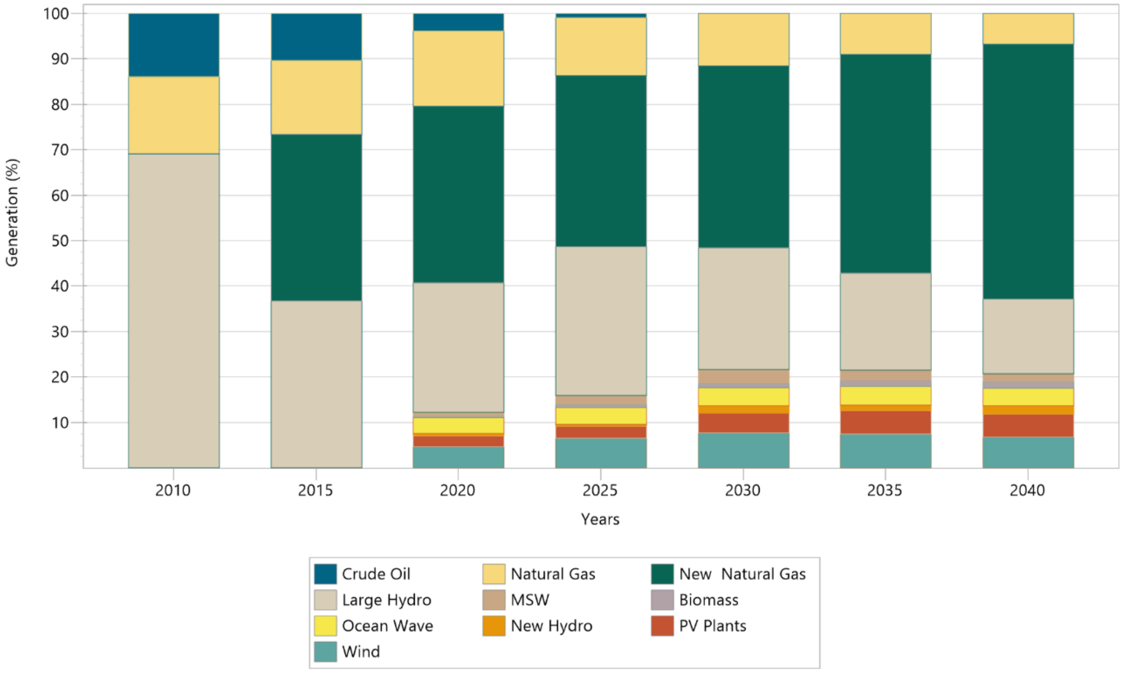


Figure 5-7 Percentage share of capacity by plant type in modest RET scenario

The exogenous capacities of PV and wind plants considered in the modest RET scenario were higher than that of tidal waves plants. Maximum capacities of 2000 MW and 1500 MW were considered for PV and wind respectively, while 500 MW was considered for tidal wave plants. Detailed transformation data used in the model is presented in Appendix E. The higher availability factor of tidal waves plants compared to that other NRET have however, resulted in its relatively high output.

Municipal Solid Waste (MSW) plants and small hydro are introduced into the generation mix in 2020 with capacities of 50 MW and 20 MW respectively, expanding to 300 MW and 200 MW respectively in 2040. Despite the expansion in renewable technologies, the total share of renewable generation reduced to 38% at the end of the study period compared to the base case share of 68%. This was due to the marginal expansion in large hydro plants which provided almost 100% share of the renewable generation in 2010 due to the near exhaustion of this resource.

5.2.1.4 Technical results of High RET scenario

The high RET scenario assumes a generation policy that makes maximum use of the available renewable energy resources of the country and a reduction in the use of fossil fuels. In addition to the high increase in NRET, the scenario also considered the construction of two new hydro plants in 2025 and 2035. Figure 5-8 illustrates the generation by plant type in the high RET scenario. The expansion plan adopted in the high RET scenario resulted in curtailment in thermal generation. Renewable energy technologies thus dominate the generation system with an average share of about 55% throughout the study period.

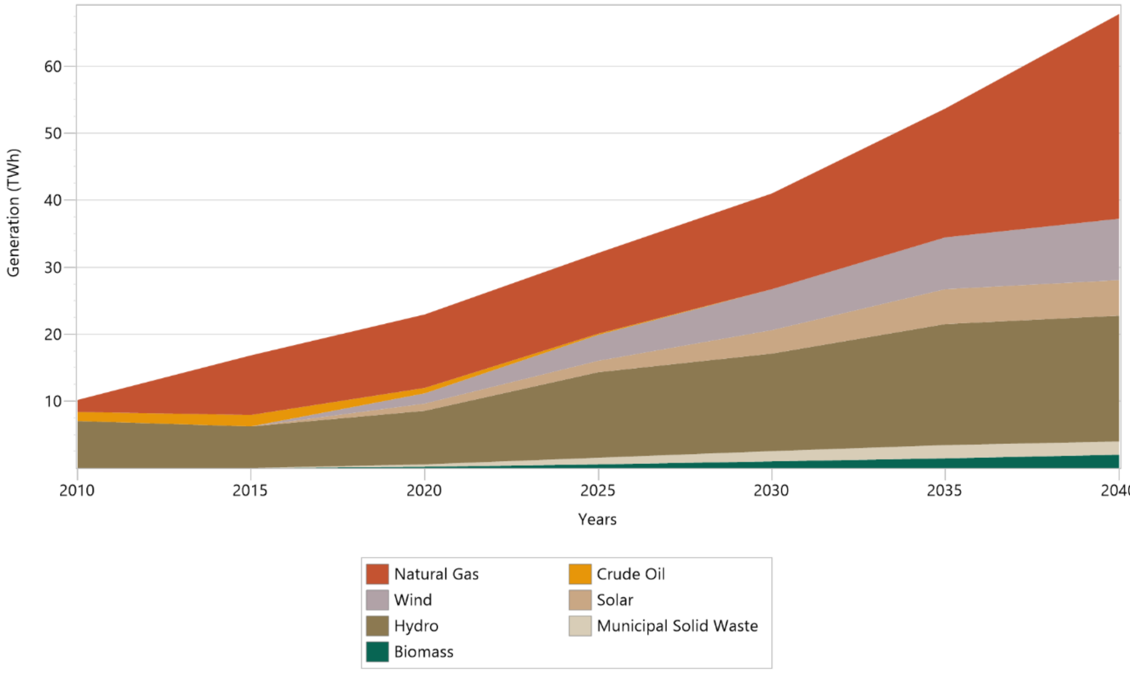


Figure 5-8 Generation by feedstock fuel for moderate renewable scenario

The increased deployment of renewable energy technologies has, as anticipated, increased NRET share to a maximum share value of 42% in 2030 largely from wind, PV and hydro sources. This share however reduced slightly to 37% in 2040. The percentage contribution by plant type is illustrated in Figure 5-9.

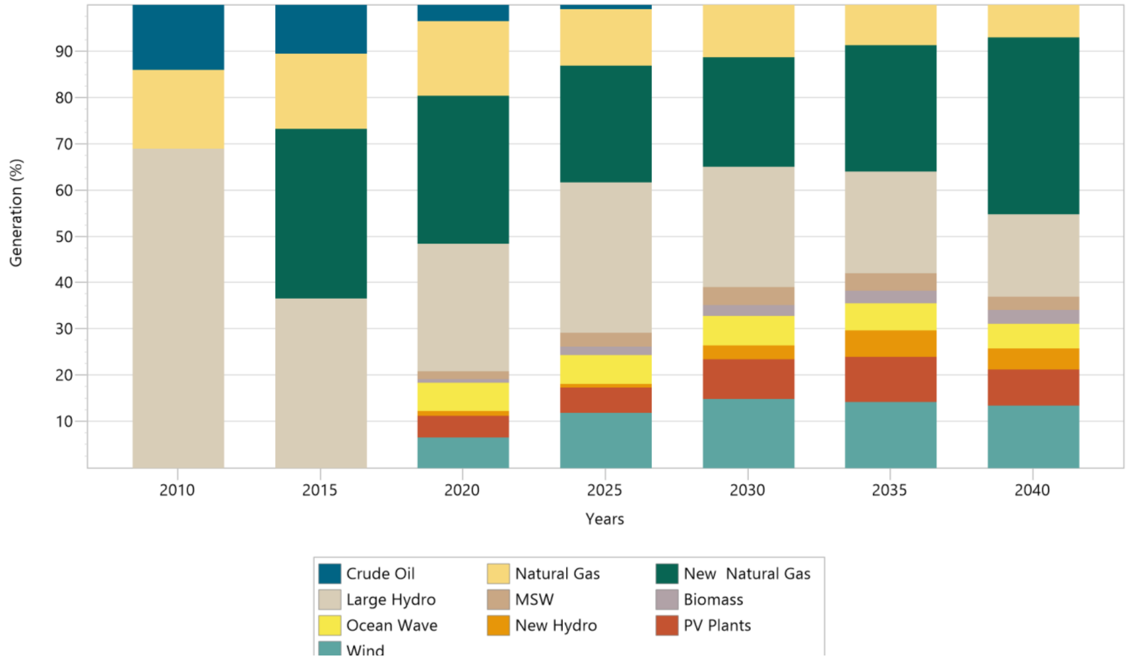


Figure 5-9 Generation share by plant type in high RET scenario

Unlike in the other scenarios, the capacities of renewable technologies in the high renewable scenario peaked at values close to the confirmed realistic maximum available resource of the various plant types. These results therefore reveal that based on the current demand growth Ghana can continue to meet more than 50% of its generation requirement from renewable energy technologies. It is important to note that the stability of the grid system with a high penetration of intermitted renewable technologies such as wind and PV was not considered in this thesis as it is beyond the scope of the thesis and will be considered as an extension to this research work.

5.2.2 Cost-Benefit Analysis of the Scenarios

The economic results of the scenarios expressed in 2010 US dollars, are presented in Table 5-1. Operation and maintenance (O & M) cost includes both fixed Operation and maintenance and variable Operation and maintenance. Environmental Externalities (Env. Ext.) costs were also captured to enable a quantification of the environmental effect of the scenario. The generation of power from fossil fuel leads to emission of greenhouse gases, which has an adverse effect on society. The cost of these negative consequences therefore needs to be considered when appraising generation technologies. Currently, Ghana does not have a carbon tax mechanism in place; however, the study assumes an introduction of $10/tonne carbon tax in 2020 rising to $20/tonne in 2030. The aim of this current study is not to achieve a level of carbon pricing that will overcome externalities associated with power production in Ghana but rather highlight the effect of the introduction of carbon tax on the various scenarios. Revenue from the sale of electricity was not captured in this analysis. This is because the same demand was applied to all the scenarios and the scenarios were modelled to meet this demand as well as the specified reserved margin. Thus, the cost-benefit summary in Table 5-1 expresses only the avoided transformation cost, fuel purchased and environmental externalities cost compared to the base case scenario. These results may therefore not indicate the exact cost values for the scenarios; however, they provide useful benchmark for comparing their economic performance.

Table 5-1 Cumulative discounted cost benefits 2010 to 2040 relative top base case scenario

Cost (Million US$)	5% Discount Rate			10% Discount Rate			15% Discount Rate		
	Coal	**Modest RET**	**High RET**	**Coal**	**Modest RET**	**High RET**	**Coal**	**Modest RET**	**High RET**
Transformation	467.5	2120.4	6249.3	180.6	787	2407.6	81.6	310	1053.6
Fuel	-1815.2	-3757.9	-8238.5	-685.7	-1290.1	-2856.7	-299.4	-497.4	-1115.8
Env. Ext.	120.7	-213.4	-465.8	40	-72	-157.8	14.8	26.9	59.4
NPV	**-1227**	**-1850.9**	**-2455**	**-465.1**	**-598.1**	**-607**	**-203**	**-214.3**	**-121.5**

It is observed from Table 5-1 that the capital and O&M costs of the alternative scenarios are higher than the base case scenario. At the reference discount rate (10%), an extra $787 million and $2408 million in capital investment will be required to implement the modest RET scenario and the high RET scenarios respectively over the 30 year study plan considered. A real discount rate of 10% was used based on the West Africa Power Pool generation and transmission master plan recommendations for member countries [134].These results were not surprising considering the higher investment cost of technologies considered in the alternative scenarios. The results also show that the total Net Present Value (NPV) of the cost of the RET scenarios were lower than both the base case and coal scenarios. This is due to the significant savings in cost of fuel that occur in the two RET scenarios. These results show that the current generation system plan of Ghana (Base case scenario) is the obvious choice when consideration is given to only investment cost. However, the long-term savings in fuel cost by the alternative scenarios over the study period of 2010–2040 increasingly makes the higher integration of RET into the generation plan a viable alternative. The trend in cumulated discounted cost/benefits of the scenarios over the study period is illustrated in Figure 5-10.

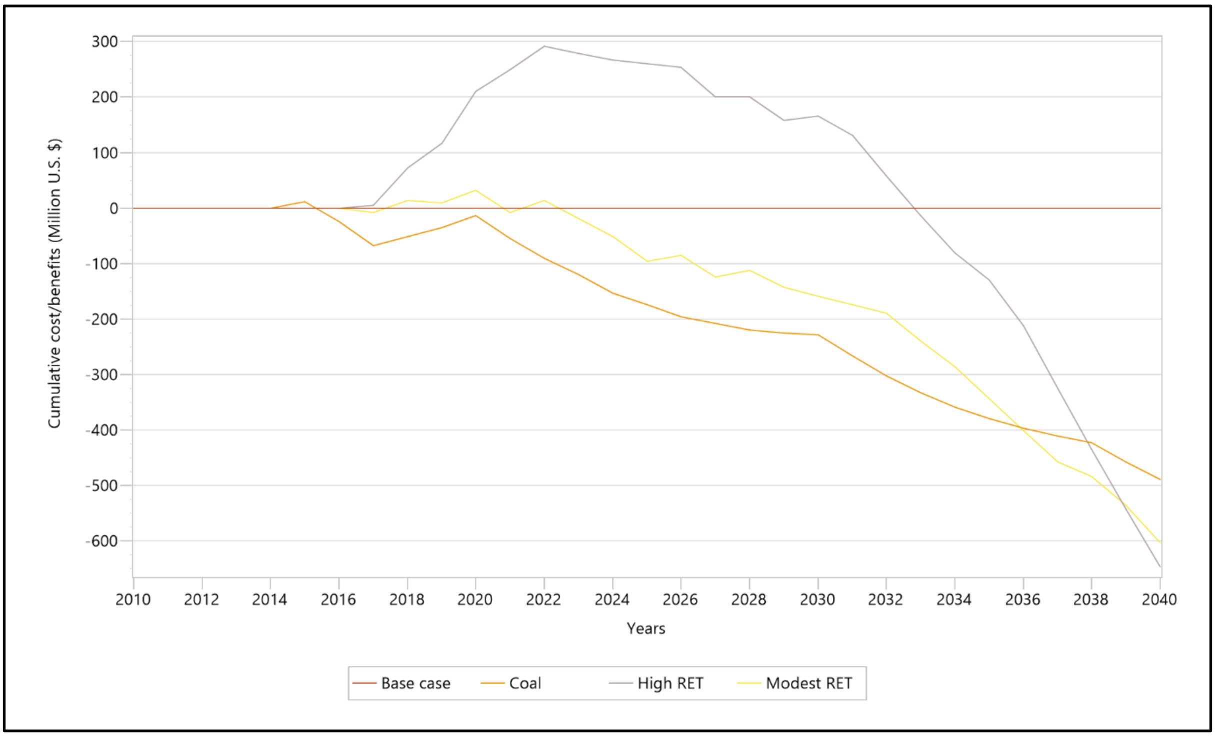


Figure 5-10 Cumulated discounted cost benefits of scenarios (Discounted Rate =10%)

The results in Figure 5-10 show that economic benefits due to savings in fuel cost could be achieved in the short term with modest introduction of renewables. However, high RET scenario will begin to yield economic benefits beyond 2033. This means that based on the assumptions and constrains used in developing the scenarios, RET can be deployed in the Ghana generation mix on their own merit with guaranteed long term benefits.

Table 5-1 further compares the NPV of the alternative scenarios under discount rates of 5% and 15%. An immediate observation of the trend in NPV seems to suggest that the choice of discount rate does not significantly affect the choice of the alternative scenario compared to the base case as a similar trend was observed. However, an analysis in terms of the cumulative NPV compared to the base case clearly shows that the lower the discount rate, the higher the present value of the future cash flows. It is observed from Table 4 that lower discount rate favour the RET scenarios which are dominated with highest capital intensive technologies. A key policy priority should therefore be geared towards the provision of guaranteed long term finance to promote the high integration of RET.

5.2.2.1 Effect of RET investment and fossil fuel cost on the economic performance of scenarios

The cost of fossil fuel was considered as the most important parameter that influences the cost of generation of the thermal plants, while that of RET is largely dependent on investment cost. These two parameters also have high variability in price: while the cost of RET especially wind and solar have seen a downward trend in capital cost; that of fossil fuel price is generally unstable. To this end, sensitivities on the capital cost of RET and cost of fossil fuel were undertaken to determine the effect of variation of these parameters on the economic performance of the scenarios.

Table 5-2 presents the NPV of the scenarios under the various fossil fuels and RET investment cost sensitivities. The top part of the table shows the cumulative NPV in 2010 billion US dollars, while the bottom part compares the NPV of the alternative scenarios to the base case.

Table 5-2 Economic performance with fuel and RET investment cost sensitivities[7]

	NPV (Billion 2010 US$)			
	Base	**Coal**	**M. RET**	**H. RET**
LF + LR	15.43	15.24	14.86	13.95
HF + LR	19.50	19.06	18.57	16.92
LF + HR	15.94	15.76	15.86	15.82
HF + HR	20.00	19.56	19.56	18.77
	Percentage change			
LF + LR	0	-1.23	-3.69	-9.59
HF + LR	0	-2.26	-4.77	-13.23
LF + HR	0	-1.13	-0.50	-0.75
HF + HR	0	-2.2	-2.2	-6.12

It is observed from Table 5-2 that the alternative scenarios are less expensive compared to the base case over the study period. This is mainly due to the higher fuel savings in the alternative scenario with increase in fuel cost. This trend is similar to the trend in Table 5-1and seems to suggest that variation in fuel and RET investment cost does not significantly affect the comparative performance of the scenarios. However, a closer look at the percentage change of NPV compared to the base case shows a better understanding of the variation. Modest RET scenario's will be 3.69 – 4.77% less expensive, while that of High RET will be 9.59 –13.23% less expensive compared to the base case.

It was however surprising to note that RET scenarios resulted in higher benefits with higher fuel prices. This was evident with the highest savings for the alternative scenarios occurring with HF + LR sensitivity. It can thus be suggested that the inclusion of modest to high RET into the generation mix of Ghana will not only help to diversify the generation system but will also lead to economic benefits of between 0.5% and 13.23% depending on the development of fuel and RET investment cost. This finding has important implications for developing of RET by

[7] key: LF = Low fuel cost; HF = high fuel cost; HR = high NRET investment cost; LR = low NRET investment cost

showing that based on the current economic trends, technologies and energy resources in Ghana, higher penetration of RET is competitive on its own merit to conventional expansion when considered over a 30 year period.

5.2.3 Environmental Analysis of the Scenarios

The Fourth Assessment Report (AR4) emission factors were adopted for this study. This is in line with IPCC's (2013) conference of parties (COP 19) guidelines, which recommends that as of 2015, national communications should use the AR4 factors to ensure uniformity in reporting [135]. The cumulative GHG emissions of the scenarios compared to base case scenario are presented in Figure 5-11.

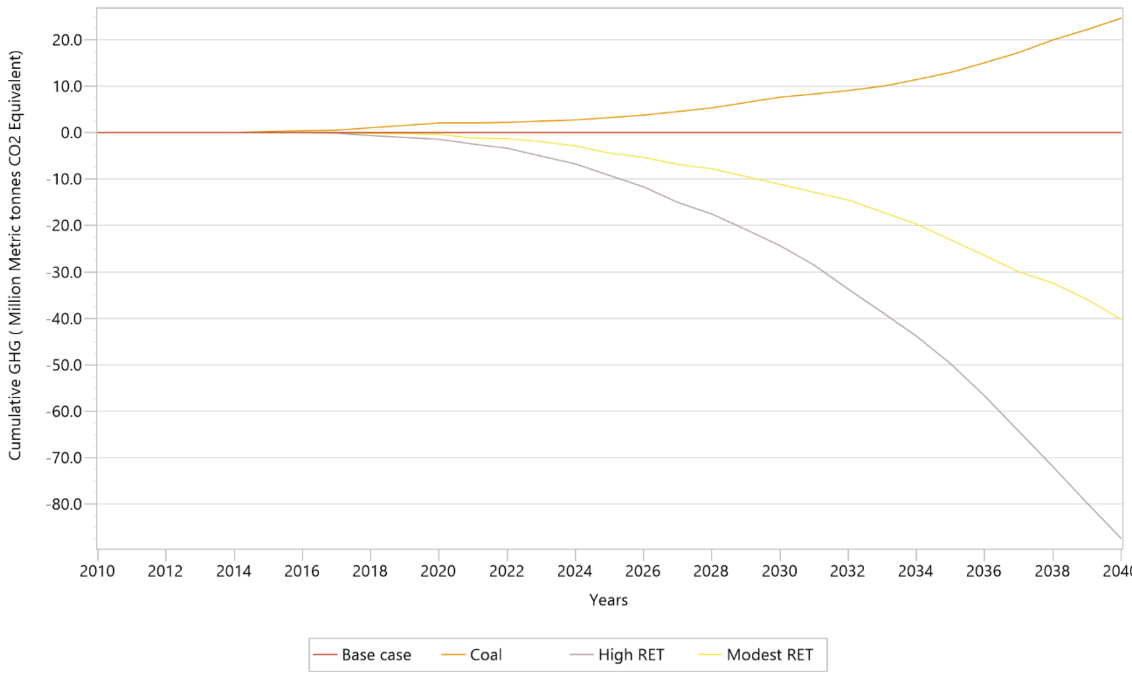


Figure 5-11 Cumulative GHG emissions compared to base case scenario

The environmental effect of the introduction of coal is evidenced by the higher emission of the coal scenario compared to the cleaner NG generation in the base case. The only difference between the coal and base case scenarios is the endogenous addition of coal plants to take up a maximum of 20% of new natural gas plants share. The introduction of coal is evidenced with cumulative emission of about 30 MMtCO_2e (million metric tons carbon dioxide equivalent) compared to base case as shown in Figure 5-11.

There is currently no enforcement of CO_2 emissions limitation on power generation plants in Ghana. This is because of the comparatively lower emission levels in the country. This has informed the continuous expansion of thermal plants as represented in the base case scenario. Coal, which has presently topped the list of possible candidate plants, will lead to higher emission levels in the country. The contribution of coal generating plants to global GHG emissions is further highlighted in the IEA's world energy report [136]. According to the IEA [136] , even though coal share of world generation in 2009 was 41%, it accounted for 73% of the world 11.8 Giga tonne of CO_2 emissions for that year. Aside the major GHG, coal ash, which is solid waste produced after combustion, contains many toxins including arsenic, cadmium, selenium. The adoption of the coal scenario will therefore be at the expense to the environment. It is important for the country to consider the introduction of emission standards with the liberalisation of the energy sector to encourage independent power producers to not only invest in renewable energy but to continue to explore more efficient thermal generation such as combined cycle gas plants.

Figure 5-11further confirms the general idea of the contribution of renewable energy technologies in the reduction of CO_2 emissions. The results show that if the country could afford to follow the generation expansion plan proposed in the high RET scenario, about 90 MMtCO_2e will be avoided over the study period, a reduction of about 40% to the base case plan. It is however essential to further analyse the environmental effect of high introduction of biomass generation which was considered in higher capacities in the RET scenarios. This is because biomass generation leads to higher emission of photochemical oxidation (POCP) and Eutrophication [137] as well a source of particulate matter (PM1, PM2,5, PM10) and heavy metals [138]. Over exploitation of forest reserves leading to deforestation is also possible with biomass generation. These negative implications were not considered in this study. There will therefore be the need to further assess this renewable energy source if the scenarios proposed in this study are to be adopted for implementation. However, Paiano and Lagioia [138] suggested that innovation in bioenergy conversions could control these emissions, while the cultivation of dedicated energy crops for power generation may help to solve the problem of deforestation [139].

The environmental results in LEAP can also be expressed in terms of cost of avoided CO_2 emission. Cost of CO_2 avoided is the cost of reducing CO_2 emission to the atmosphere expressed as $/tonne of CO_2 not emitted with respect to the base case scenario. The decision criterion is to identify the least cost alternative in reducing a tonne of CO_2. The results of the cost of CO_2 avoided under different discount rates are shown in Table 5-3.

Table 5-3 Cost of avoided CO_2 emissions (US $/tonne of CO_2eq)

	Discount rate (%)		
	5	10	15
Modest RET	- 46.15	- 14.91	- 5.34
High RET	- 28.06	- 6.94	- 1.39

It is interesting to note that even though the GHG savings is higher in the high RET scenario, the modest RET scenario results in net higher benefits at 5% and 10% discount rates. It should be noted that cost of avoided CO_2 is not applicable to the coal scenario since it resulted in higher emission compared to the base case. These results show that Ghana could secure funding through Clean Development Mechanism (CDM) under the Kyoto protocol if the country makes maximum use of its abundant renewable energy potential. CDM allows developing countries to sell carbon credits to developing countries with mandatory GHG emission reduction targets.

5.3 SUMMARY

This study explored several policy options that can be adopted to meet the increasing electricity requirements of Ghana based on the available energy resources and technologies. The chapter begins with a description of the four initial scenarios: Base case, Coal, Modest RET and High RET. Each of the scenarios represents policy options for generation expansion in Ghana up to 2040. Energy, economic and environmental analysis of the three alternative scenarios compared to the Base scenarios were undertaken. Sensitivity results show that, if the country were to follow the generation expansion path described in the renewable energy scenarios, it could reap economic benefits of 0.5–13.23% depending on the developments in fuel prices and renewable technology capital cost. The analysis further quantifies benefits to be derived from a reduction in Greenhouse gases of the scenarios.

CHAPTER 6

OPTIMISATION OF THE POWER SYSTEM OF GHANA

6.1 LEAP/OSEMOSYS OPTIMISATION MODEL

The optimisation function in LEAP is performed through integration with Open Source Energy Modelling System (OSeMOSYS) which depends on the GNU Linear Programming Kit (GLPK), for solving large linear programming problems [119]. OSeMOSYS is transparent and straightforward energy modelling tool, which allows for simple refinements for sophisticated analysis [140].

LEAP interface with OSeMOSYS provides a transparent connection, which enables LEAP to automatically write data files needed for OSeMOSYS. This enables LEAP users to perform optimisation without directly interacting with OSeMOSYS or GLPK [119]. A diagrammatic representation of the integration of OSeMOSYS into LEAP is presented in Figure 6-1 Integrating OSeMOSYS into LEAP

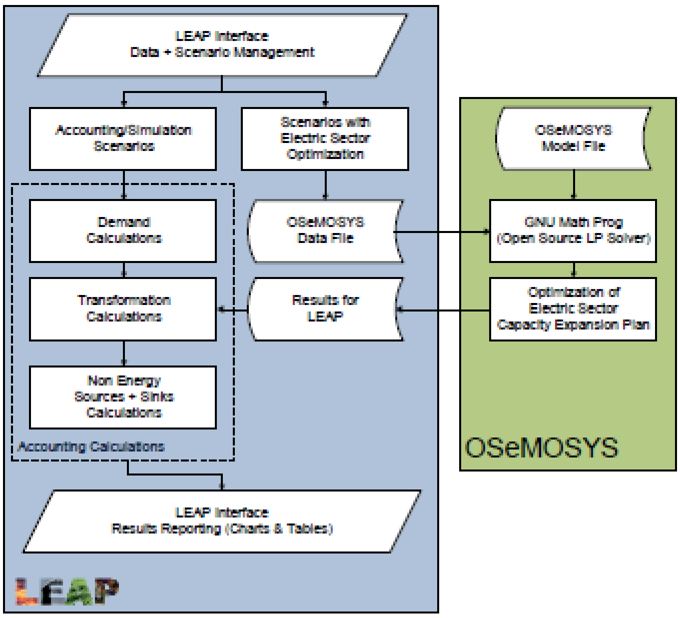


Figure 6-1 Integrating OSeMOSYS into LEAP [119]

Leap automatically writes data files required by OSeMOSYS by making used of the same data inputs in its own interface. LEAP supplies the data to OSeMOSYS in a single text file, which is processed by GLPK[8]. GLPK requires a model, which describes objectives, variables and their relationships. OSeMOSYS then generates an intermediate file, which can be read by a solver from the input data. OSeMOSYS makes use of open source lpsolve[9] (Linear Programming solver) for optimisation. Lpsolve is a Mixed Integer Linear Programming (MILP) with a powerful API (Application program interface), which can be called from many programming languages. The solver after finding the optimal solution, writes a text file (.txt) containing the set of results. Finally, the optimisation results are read back into LEAP and view in LEAP's standard results reports.

The optimisation function in LEAP is used to calculate the least-cost expansion and dispatch of power plants in an electric system. Optimal in this case is defined as the energy system with the lowest total net present value of the social cost of the system over the entire period of the calculation [119]

LEAP considers all the relevant cost and benefits incurred in the system when calculating the optimal system including:

- Capital cost of constructing new processes
- Salvage values or decommissioning cost
- Fixed and variable operational cost

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[8] See http://www.gnu.org/software/glpk/glpk.html for a complete description of this modelling language

[9] http://lpsolve.sourceforge.net/5.5/

- Fuel cost
- Environmental externalities

The least cost can optionally be calculated subject to a number of user-defined constraints such as minimum and maximum capacities of plants, emission targets and minimum renewable standard.

6.1.1 Algorithm of the LEAP/OSeMOSYS Optimisation Model

6.1.1.1 Objective function

The objective function of the OSeMOSYS model is to estimate the generation system to meet demand by minimising the total discounted cost [141]:

$$[\, Minimise \sum_{y}\sum_{t}\sum_{r} DTC_{y,t,r} = DOC_{y,t,r} + DCC_{y,t,r} + TEP_{y,t,r} - SV_{y,t,r}, \forall y,t,r \,] \qquad (6.\ 1)$$

where, DTC_{ytr}, $DOC_{y,t,r}$, $DCC_{y,t,r}$, $TEP_{y,t,r}$, $SV_{y,t,r}$ represents discounted total cost, operating cost, capital cost, technology emission penalty and salvage value respectively. *y, t, r,* are the year, technology and region indexes respectively.

6.1.1.1.a Total discounted operating cost

Operating cost is the sum of the fixed and variable operating cost. The fixed cost is determined by the capacity of the technology. The variable costs are a function of the technology's activity level during a time slice [140].

$$DOC_{y,t}(US\$) = Ca_{y,t} \times FOC_{y,t} + \sum_{l}(AL_{y,l,t} \times VC_{y,t} \times YS_{y,t}) \qquad (6.\ 2)$$

where Ca, FOC, AL, VC, YS represent total installed capacity, fixed operating cost, activity level, variable cost and year split (fraction respectively, and l is the time slice index.

6.1.1.1.b Total capital cost

Capital cost are calculated by finding the product of capacity requirements (NC) and their respective capital costs (CC). They are then discounted [140].

$$DCC_{y,t}(US\$) = CC_{y,t} \times NC_{y,t} \times DF_{y,t} \tag{6. 3}$$

Where DF represents the discount factor.

6.1.1.1.c Salvage value

Salvage value is the value of each technology remaining at the end of the modelling period. The net present value (NPV) salvage value is calculated by technology in the year in which new investment took place [140].

$$SV_{y,t}(US\$) = CC_{y,t} \times NC_{y,t} \times SF_{y,t} \tag{6. 4}$$

6.1.1.2 Constraints of the model

6.1.1.2.a Fuel production constraints

The fuel constraint is the main driver of the model. Fuel production during each time slice and year must be greater than or equal to its consumption by technologies plus any exogenous demand for that fuel.

$$\text{Production}_{y,l.f} \geq Demand_{y,l,f} + Consumption_{y,l,f} \quad (6.\ 5)$$

where:

$$\text{Production}_{y,l,f} = \sum_t \left(Activity_{y,l,t} \times OtptActivityRatio_{y,t,f} \times YearSplit_{y,l} \right) \quad (6.\ 6)$$

$$Consumption_{y,l,f} = \sum_t \left(Activity_{y,l,t} \times InptActvtyRatio_{y,l,f} \times YearSplit_{y,l} \right) \quad (6.\ 7)$$

6.1.1.2.b Capacity constraints

Each technology can accommodate an activity that uses or produces or both. The capacity of each technology must be greater than its activity for each load region.

$$Activity_{y,l,t} \leq TotalInstalledCapacity_{y,t} \times CapacityFactor_{y,t} \quad (6.\ 8)$$

6.1.1.2.c Activity constraints

In these constraints, the activity of a technology is limited by its annual availability.

$$\sum_l \left(Activity_{y,l,t} \times YearSplit_{y,l} \right) \leq TotCapAnn_{y,t} \times CapacityFactor_{y,t} \quad (6.\ 9)$$

6.1.2 Description of Scenarios

The scenarios developed in this section are based on cost minimisation with the aim of exploring the potential diversification of the generation system of Ghana using renewable energy technologies. The scenarios are categorised under four main themes: Optimisation Scenario (OPT), Carbon Tax scenarios, Energy Efficiency Scenarios, Transmission and Distribution losses scenarios and Comprehensive scenarios. The policy scenarios are all variations of the OPT under the various constraints described under each scenario. Figure 6-2 and Table 6-1 show the structure and key feature respectively, of the least cost minimisation scenarios investigated in this thesis.

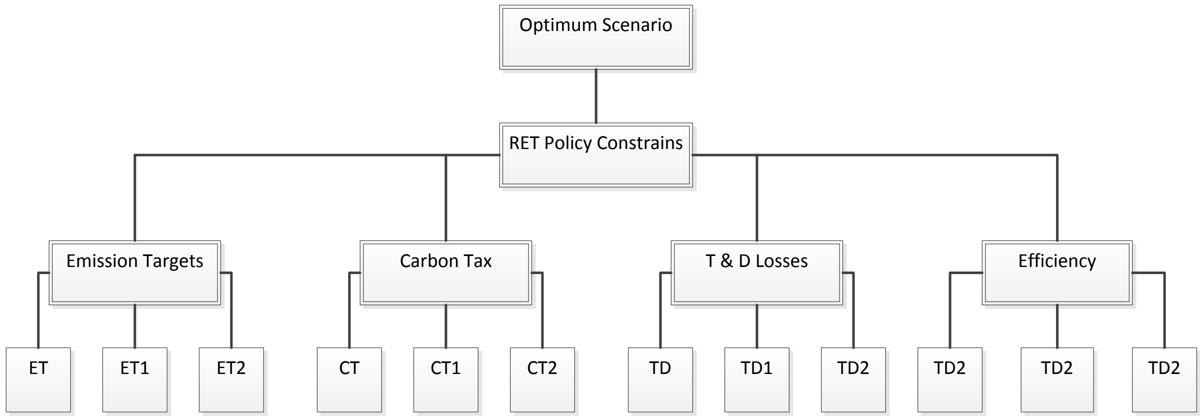

Figure 6-2 Structure of the Optimum Scenarios

Table 6-1 Main features of optimum scenarios

	OPT	Target	Carbon tax	T&D	Efficiency
Driving philosophy	Follows continues trend in existing energy policies	Inspired by clean technologies and increasing resistance from residents and environmentalist	Inspired by clean technologies and increasing resistance from environmentalist	Inspired by desire to improve the efficiency of the transmission and distribution system	Inspired by desire to improve demand side efficiency
Demand side	The Bottom-Up demand model approach in LEAP was adopted for modelling the future energy demand. Demand projections to follow official projections [16]. Total Demand in 2020 will be 18.88 GWh, increasing to 62.5 GWh by 2040.				
Supply side/ constraints	Least cost development of technologies and dispatch schedule determined by LEAP	Least cost system under emission targets constraints. maximum emission.	Least cost system under emission targets constraints.	Least cost with improvements in transmission and distribution losses.	Least cost with improvement in demand side efficiency

The scenarios represent possible future paths for promoting renewable power generation in Ghana by considering the factors most likely to influence future RET policies in the country.

6.1.2.1 Optimum (OPT) Scenario

The OPT scenario (Reference Optimum scenario) is the least cost generation system calculated by LEAP/OseMOSYS optimisation model without any policy interventions This scenario makes use of the assumptions described in base case scenario (Section 5.1.1). However, unlike the base case scenario in Section 5.1.1 where future expansions were exogenously determined, LEAP/OseMOYS developed the least cost model by deciding both the type and size of technologies as well as the dispatch scheduling.

The following additional data (Table 6-2) was applied to enable the optimisation process in LEAP.

Table 6-2 Additional Plants data for optimisation

Plant	Maximum addition (MW)	Availability (%)	Maximum capacity (MW)
Thermal	Unlimited	70	unlimited
Large hydro	0	76	1500
Ocean wave	50	60	500
MSW	100	55	1000
Biomass	100	50	1000
New hydro	100	60	700
Wind	200	35	2000
PV	500	20	10000

The maximum capacity addition was assumed based on GRIDCO [124] recommendation to ensure stability of the grid, while the maximum availability of the RET were assumed based on the confirmed available resources [4, 13].

The optimisation process of LEAP also requires load shape data. Load shape describes how the electric load varies among the different seasons and times of day. This is important in determining what mix of base load or peak load plants make should be built and operated. See Appendix E for the load shape data used for the optimisation model.

6.1.2.2 CO_2 Emission target scenarios

Global environmental concerns have necessitated the need for controlling GHG emissions. Power generation has contributed significantly to global emission. In the USA, the highest share (30%) of 2014 GHG was from electricity generation plants [142]. In Ghana, power generation has resulted in increasing GHG emission due to the expansion of fossil fuel thermal generating plants.

Ghana, being a non-annexed country has no legally binding emission reduction target in place. Thus, studies evaluating the impact of GHG mitigation are limited in the country. However, the consideration of the impact of GHG by different power generation plants will lead to a more balanced evaluation of these technologies and will also conform to the Bali road map which underscores the need for developing countries (Non-Annex I countries) to introduce mitigation actions after 2012 [11].

The study examines three CO_2 reduction scenarios which were developed making use of the OPT scenario emissions as the benchmark. They are Low Emission target (ET), Modest emission target scenario (ET1) and High emission target scenario (ET2). These scenarios impose maximum emission target of 10%, 20% and 30% respectively, lower than the OPT scenario emissions. These emission targets were based on the official targets as part of the country's Intended Nationally Determined Contribution (GH-INDC) presented to the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015 [133].

6.1.2.3 Carbon tax scenarios

The Kyoto protocol makes provisions for three market-based mechanisms CDM; joint implementation and emission trading that provide additional means for countries with commitment to achieve their set targets. These mechanisms have resulted in the creation of the “carbon market” which enables international trading of emission target points [143]. CDM specifically targets emission reduction projects for developing countries. CDM allows Annex I countries to participate in the implementation of emission reduction projects in non-annex I countries. These projects are then assessed as supplementary to domestic project, to help achieve their targets. Ghana can therefore benefit significantly from these mechanisms to help develop its abundant renewable energy resources, if the cost of domestic GHG emission reduction is lower than the global carbon price.

Another important source of funding for renewable energy development is the introduction of carbon tax. High investment cost of RET has been cited widely as one of the most important obstacles hindering their development in the developing world including Ghana. Additional revenue from the implementation of carbon tax could be applied directly to the development of RET. Introduction of carbon tax will also provide a fair appraisal for assessing the performance of different generation technologies. Therefore, three carbon tax scenarios explored in this study. Low Carbon Tax (CT) scenario imposes US$10/tonne CO_2 introduced in 2020 increasing to US$20/tonne CO_2 in 2030; Modest Carbon Tax (CT1) imposes US$30/tonne CO_2 introduced in 2020 increasing to US$60/tonne in 2030; High Carbon Tax (CT2) imposes US$50/tonne CO_2 introduced in 2020 increasing to US$100/tonne in 2030.

6.1.2.4 Transmission and Distribution Losses Scenario

In 2010, Transmission and Distribution (T&D) losses accounted for about 23% of the total power generation in Ghana, a reduction from a peak of 29% in 2003. However, between 1970 and 2000, these losses varied from 4 – 11% [144]. The current high T&D losses are due to large non-technical losses (mainly because of theft and non-payment of bills) [4]. The average value of the technical losses (losses due to current flowing through the network) was about 5% between 2010 and 2014 with a long-term projection of 3% [124].

The T&D scenario therefore assumed improvement in the transmission and distribution networks and billing system resulting in reduction in these losses. This was interpolated to reduce to 15% in 2020 and 10% in 2030 in Low Transmission and Distribution scenario (TD). In the Modest Transmission and Distribution scenario (TD1), the T&D losses were interpolated to reduce to 12% in 2020 and 8% in 2030. While in the High Transmission and Distribution scenario (TD2), it was interpolated to reduce to 10% in 2020 dropping further to 5% by 2030%.

6.1.2.5 Energy efficiency scenarios

This scenario considers strict implementation of energy efficiency strategies in all sectors of demand. Ghana has recently adopted a number of strategies to improve efficiency in the demand side. Notable among them is the replacement of filament bulbs with Compact Fluorescent Lamps (CFL) and refrigeration efficiency schemes [17]. These strategies have resulted in significant energy savings in demand side.

Three energy efficiency scenarios therefore assume the implementation of various strategies to improve demand sector efficiency. Low Energy Efficiency (EE) proposes low improvement in demand sectors efficiency resulting in 20% reduction in demand over the BCO scenario in 2020, improving further to 30% by 2030. Modest Energy Efficiency (EE1) pursues moderate demand side strategies leading to 20% reduction in demand over the BCO scenario in 2020, improving further to 30% by 2030. High Energy Efficiency (EE2) pursue aggressive demand side efficiency strategies and as well as high introduction of solar PV for domestic applications resulting in 20% reduction in demand over the BCO scenario in 2020, improving further to 30% by 2030.

6.2 TECHNICAL RESULTS

6.2.1 Technical Results of Optimum (OPT) Scenario

The optimum scenario (OPT) predicts a switch from hydropower generation to natural gas thermal generation in the OPT scenario as illustrated in Figure 6-3.

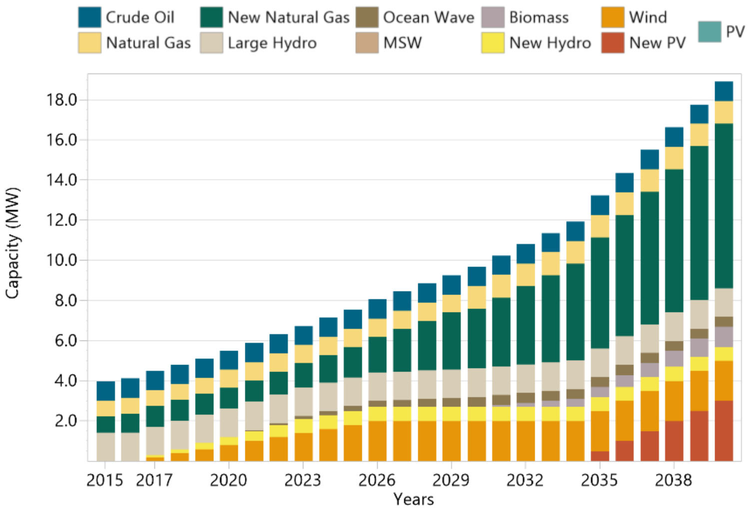

Figure 6-3 Installed capacity in OPT scenario

Two main fuel types were considered for the combineb cycle thermal generating plants considered in the model. The results show that thermal generation in Ghana will continue to be dominated by natural gas fuelled systems. Even though the same operating characteristics were modelled for both crude oil and natural gas plants to reflect the co-firing nature of the thermal plants in the country, the model did not consider operating the plants on crude oil as one of the least cost options. This is mainly due to the comparatively higher cost of crude oil. These results give credence to proposals by the EC to operate the thermal plants on natural gas when available [4].

Figure 6-3 also shows the economic competiveness of the NRET with the introduction of these systems in much larger quantities from 2016 onwards. The model considered the introduction of wind and small hydro plants in 2016. This means that Wind and Small hydro are the least cost options of the NRET. Wind energy plants capacity increased from 200 MW to its maximum allowable capacity in 2025. PV generating plants, which dominated the NRET capacity at the end of the study period, were not considered until 2035, when the model had exhausted the available capacity for wind, hydro, wave and biomass generating systems. The model did not however consider MSW as one of the least cost options for power generation in Ghana due to their extremely high investment cost.

The share of NRET generation in 2010 was 0.059%, which increased to 30% in 2023 because of the introduction of wind and hydro as discussed earlier. This share however, reduced to 25% in 2035, increasing marginally to 27% at the end of the study period with the addition of new PV systems as shown in Figure 6-4.

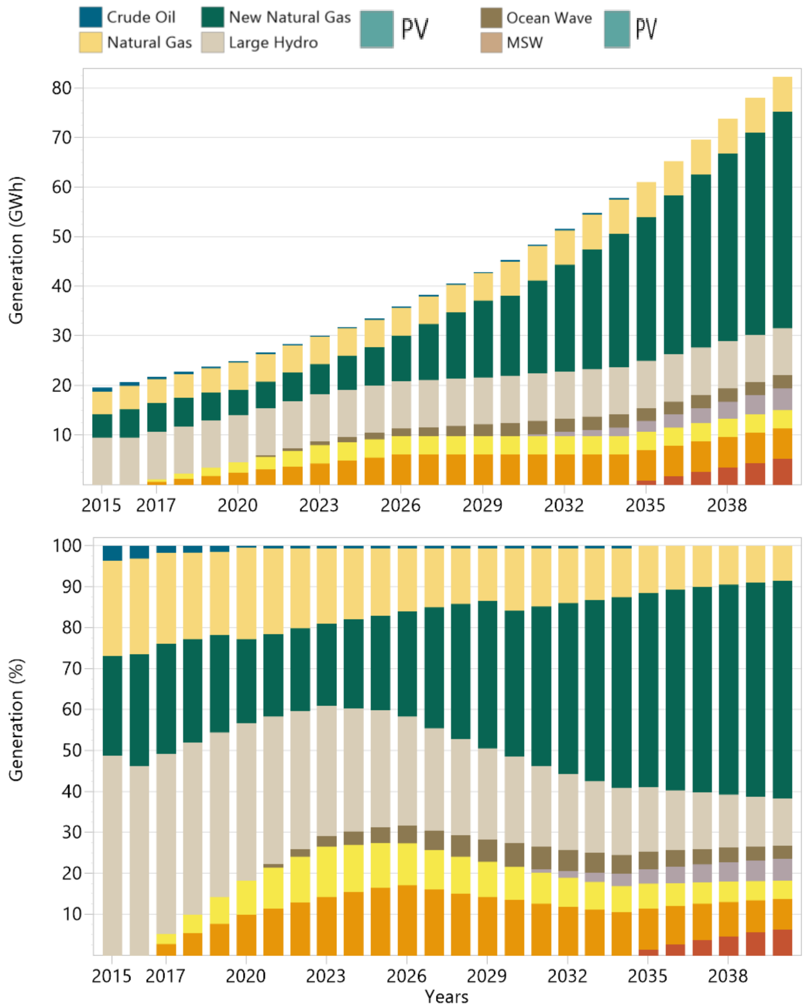

Figure 6-4 Electricity generation by plant type in OPT scenario

It is very important to note that the introductions of these NRET were based on their own economic merits. This clearly shows the high potential of diversifying the generation system of Ghana with appropriate renewable energy policies.

6.2.2 Technical Results of CO_2 Emission Target Scenarios

The introduction of CO_2 emission targets directly affects the development of clean energy technologies. Figure 4 shows the development of the optimum generation system of Ghana under the three CO_2 emissions constrains. The introduction of these targets resulted in much higher deployment of NRET. Compared to OPT scenario, the model predicted additional 1.5 GW, 3.5 GW and 7 GW NRET generation capacities in the ET, ET1 and ET2 scenarios respectively, by 2040.

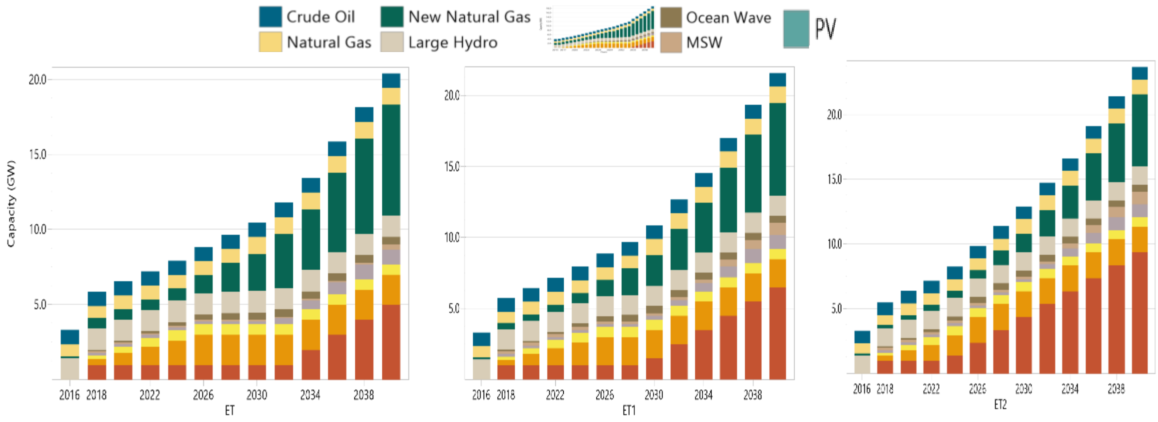

Figure 6-5 Installed capacity in CO_2 emission target scenarios

The high NRET have resulted in a total renewable generation capacity share ranging from 54 – 68% with the introduction of 10 – 30% emission reduction targets on the Optimum scenario.

New PV generation plants, which were not considered by the model in the OPT scenario until 2035, are selected at the same time with wind and new hydro plants, with the introduction of carbon emission targets. In the ET scenario, New PV were introduced in 2017 with a capacity of 0.5 GW, increasing to 1 GW in 2018 and remaining constant until 2030, when wind and hydro resources have been fully exploited. The same trend is observed in the ET1 and ET2 scenarios. However, much higher PV capacity addition is achieved with the introduction of high renewable target (ET2 scenario).

Municipal solid waste (MSW) generation plants, which were not selected in the OPT scenario because of their relative high cost of investment, are forced onto the generation mix with the introduction of carbon tax. MSW generation starts with a capacity of 0.1 GW in 2017, increasing to 0.3 GW in 2040, with a low emission target. Modest and high emission targets will lead to 0.85 GW and 1GW MSW plants capacity by the end of the study period. The developments of the renewable generation systems have reduced the share of generation from fossil fuel plants. Electricity generation from thermal generation plants in 2040 reduces from 62% in the OPT scenario to between 55 – 42% with the introduction of emission reduction targets as shown in Figure 6-6.

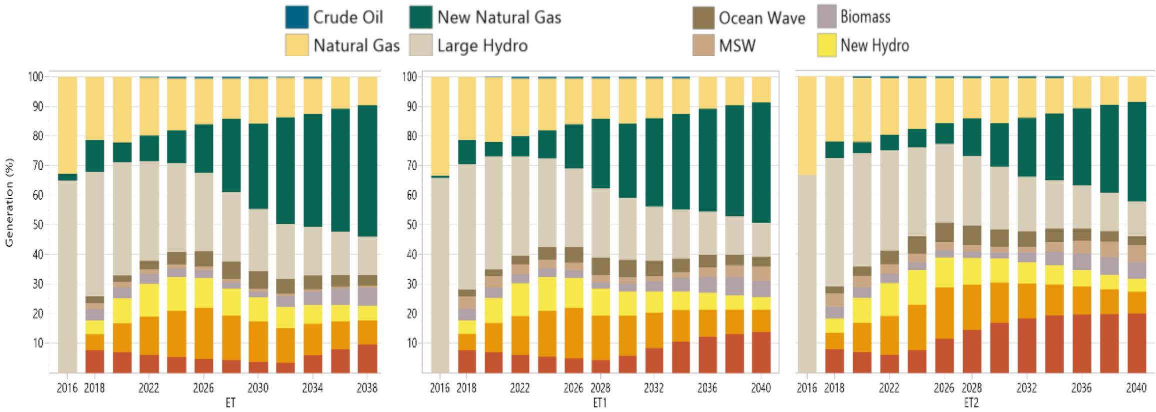

Figure 6-6 Generation share by plant type in CO_2 emission target scenarios

This reduction in thermal generation directly reduces the quantity of fuel imports for power generation. This implies that CO_2 targets have a positive impact on energy security of Ghana. This security of the energy system in this case is analysed in terms of self-sufficiency and diversification of energy resources.

6.2.3 Technical Results of Carbon Tax Scenarios

The carbon tax scenarios examine the effect of the introduction of carbon tax constraint on the optimum generation system of Ghana developed by the Ghana LEAP model. The study evaluated three tax levels: CT, CT1 and CT2, representing low, modest and high carbon tax respectively. Figure 6-7 shows the development of the optimum generation system from 2015 to 2040 under the various carbon taxes constraints.

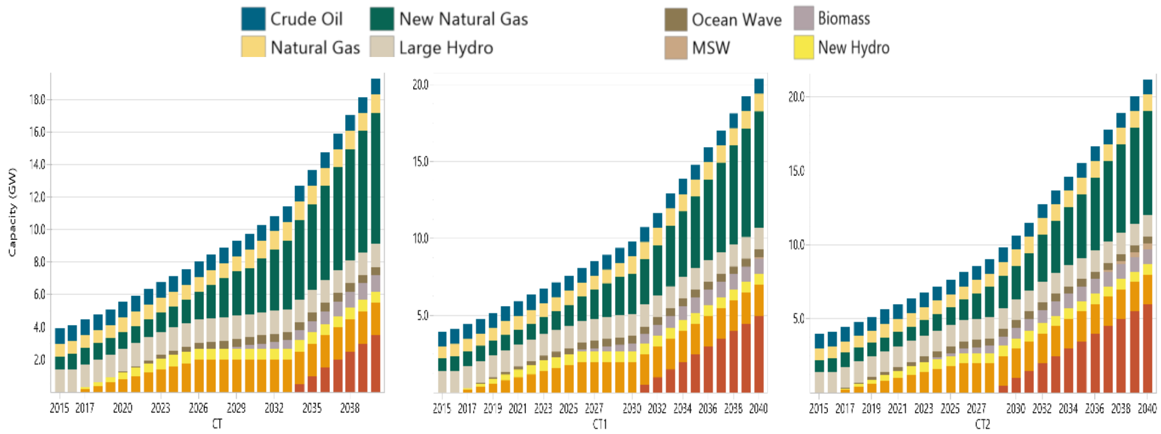

Figure 6-7 Installed capacity in CO_2 tax scenarios

It is observed from Figure 6-7 that the capacity level of conventional large hydro generation did not change within the study period. However, thermal generation capacity slightly decreases with increase in carbon taxes. The share of thermal plants decreases by about 10% with the introduction high carbon tax (CT2) Scenario. This will translate to about 10% savings in fossil fuel requirement for power generation.

Electricity generation from thermal plants reduced by about 17% to 43 TWh in the CT2 scenario compared to the OPT scenario in 2040 as illustrated in Figure 6-8. On the other hand, generation from renewable sources increased from 32 TWh (38% share of generation) in the BCO to 39 TWh (47% generation share) in CT2 scenario by 2040.

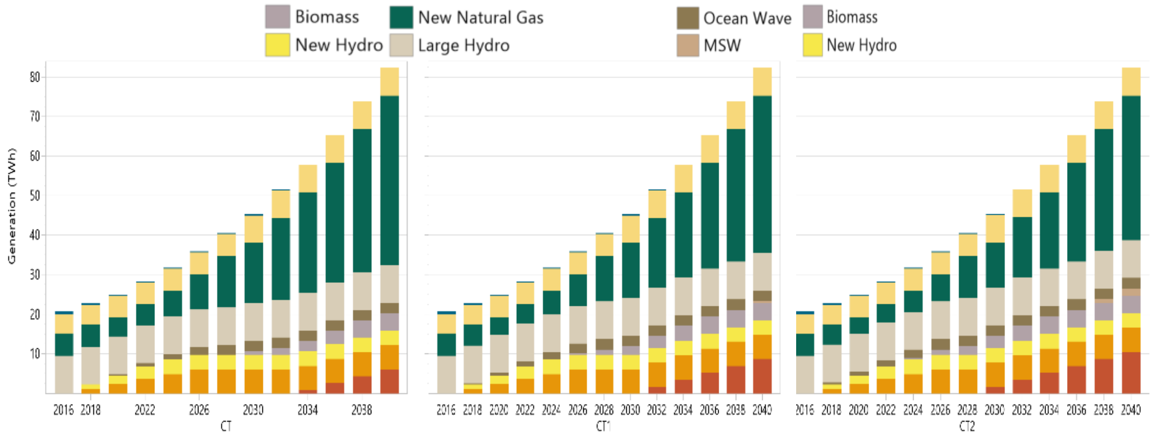

Figure 6-8 Electricity generation by plant type in CO_2 tax scenarios

These analyses clearly show that the introduction of carbon tax has direct impact on the development of renewable energy technologies. This is because renewable energy technologies such as wind and PV produce very little to zero GHG emissions. The imposition of carbon tax will affect mainly the cost of production of the thermal plants and thus makes the RET more economically viable.

A comparison of Figure 6-3, Figure 6-5 and Figure 6-7 show that both carbon tax and CO_2 emission target scenarios resulted in higher capacities compared to OPT scenario. This is because of their higher renewable energy penetration. The cumulative installed capacities of the CT2 and ET2 scenarios in 2040 are 11% and 26% respectively more than the Ref scenario. These findings are consistent with those of McPherson & Karney [58], which suggest that higher capacities of NRET are required to meet the same demand as thermal plants because of the relatively lower capacity factors of NRET.

6.2.4 Technical Results of Transmission and Distribution Losses Scenarios

Transmission and distribution scenarios examine the development of the optimum system with the implementation of strategies to improve transmission and distribution losses. As anticipated, improvement in transmission and distribution losses will lead to lower generation requirements. Figure 6-9 show the development in generation technologies from 2015 to 2040 with improvement in transmission and distribution losses.

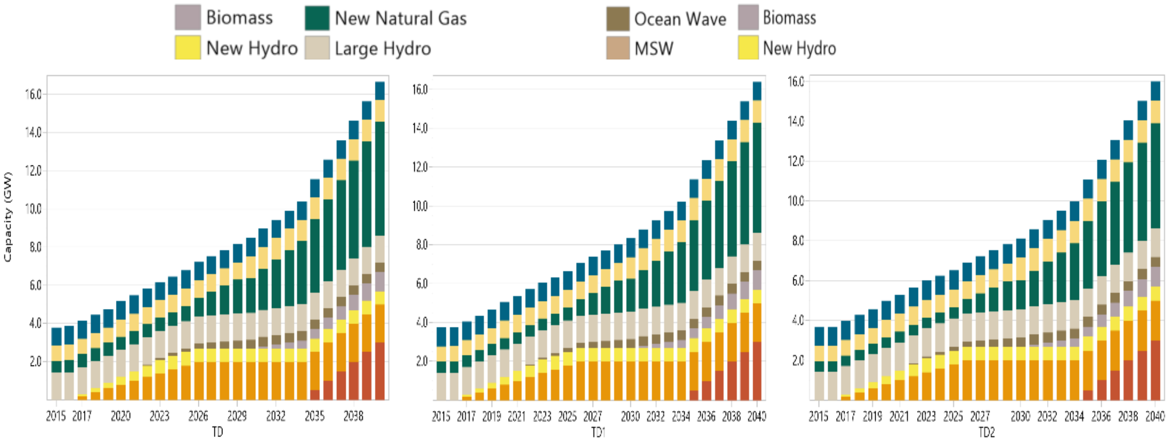

Figure 6-9 Installed capacity in transmission and distribution losses scenarios

A reduction of between 2000 MW and 3000 MW capacity is achieved depending on the level of transmission and distribution losses improvements, compared to the OPT scenario. This capacity savings is approximately equal to the current (2015) total generation capacity of the country. This shows enormous benefits of undertaking strategies to reduce the current high transmission and distribution losses. The development of the generation technologies remains almost the same as that of the OPT scenario. However, much higher renewable generation share of generation is achieve with improvement in transmission and distribution losses compared to the OPT scenario.

6.2.5 Technical Results of Energy Efficiency Scenarios

It is widely accepted that improvement in efficiency measures will lead to lower electricity demand. Figure 6-10 shows the installed capacity capable of meeting the generation requirement in the energy efficiency scenarios.

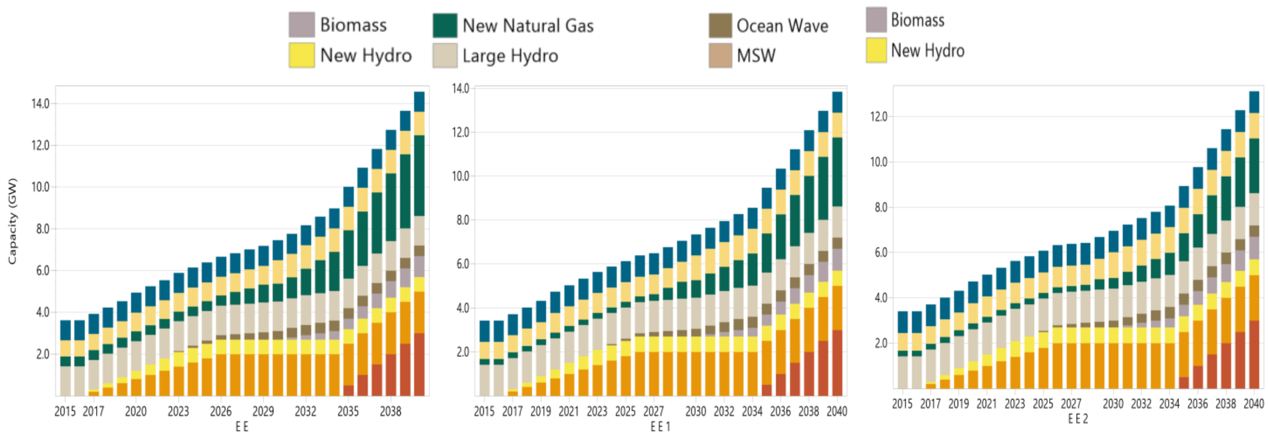

Figure 6-10 Installed capacity in energy efficiency scenarios

Comparing Figure 6-3 and Figure 6-10 shows that demand side efficiency strategies such as replacement of incandescent bulbs, refrigeration and air conditioning standards and energy labelling as well as industrial sector efficiency measures at levels implemented in the EE scenarios will result in 4350 – 5800 MW less capacity at the end the end of the study period. The capacity savings is almost twice the total capacity of the country in 2015. There is therefore the need for the country to implement demand side efficiency strategies.

The development of the generation technologies remains almost the same as that of the OPT scenario and TD scenarios. However, the share of RET generation is much higher with improvement in energy efficiency. Figure 6-11 shows the share in generation by plant type in the energy efficiency scenarios.

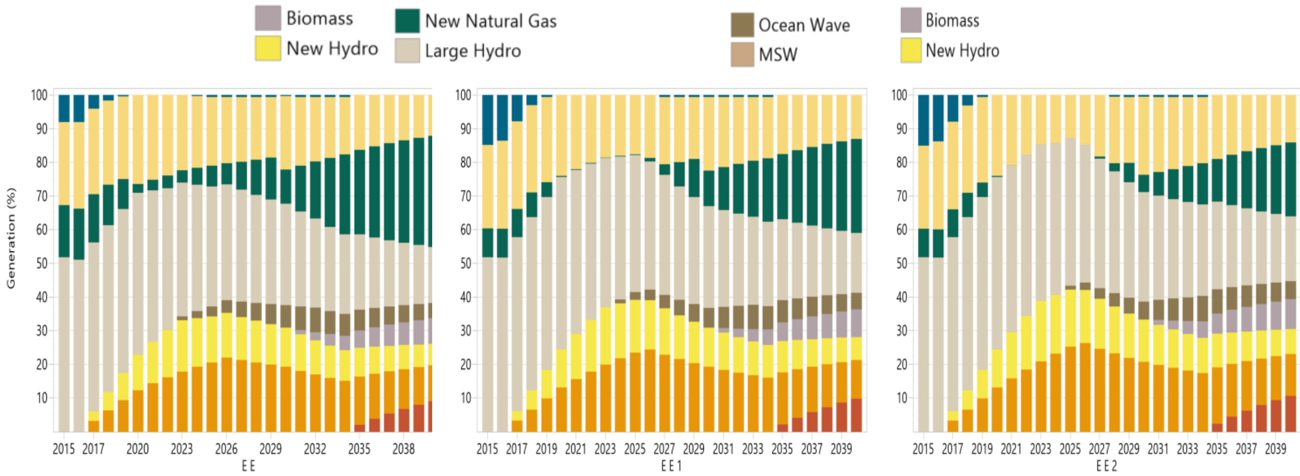

Figure 6-11 Generation share by plant type in energy efficiency scenarios

The results in Figure 6-11 show that the high implementation of energy efficiency strategies (EE2 Scenario) significantly increases the RET share of generation from 0.01% in 2015 to about 43% in 2025 and remaining almost constant until the end of the study period. The high NRET share has resulted in the total renewable generation[10] share of over 87% between 2020 and 2027 and eventually decreasing slightly to 64% in 2040. These results further underscore the need for Ghana to make energy efficiency a core of its energy strategies.

Ghana electricity generation system has relied greatly on hydropower and most recently, thermal generation plants. This has resulted in serious power outages and load shedding each time there is insufficient rainfall or inadequate supply of fuel. Introduction of renewable energy policies have resulted in higher diversification of the generation system. The level of energy security of an energy system is improved with higher diversity in energy technologies [145]. These results therefore show that

[10] This includes the conventional large hydro generation

implementation of appropriate renewable strategies will improve the security of the generation system of the country. These results however show that fossil fuel generation will continue to form an integral part of the generation system of Ghana as the renewable energy technologies cannot cater for all the future demand.

6.3 COST-BENEFIT ANALYSIS

The objective of the LEAP/OseMOSYS optimisation is to develop a least cost model of the generation system. Cost-benefits analysis technique was adopted for the economic evaluation of the various scenarios in this study. In this study, the cost of the system is expressed in terms of Net Present Value (NPV) of cost of transformation (investment and operation and maintenance cost) as well as resources (fuel cost) over the period of the study discounted at 10% to the base year. Transmission and distribution cost, land use and potential cost of affecting local livelihoods were not considered in this study. This was not only due to lack of reliable data, but also on the scope of this study, which focuses on how the various supply and demand side constraints will influence the development of generation options.

Table 6-3 presents the results of the cost-benefit analysis provided by the LEAP model. The results compare the cost-benefits of alternative scenarios to OPT scenario. A positive value represents how much more each policy scenario cost compared to the Ref scenario, while a negative number represent benefits

Table 6-3 Cumulative Costs & Benefits: 2010-2040 relative to OPT Scenario
Discounted at 10.0% to year 2010 (Billion 2010 US$)

	ET	ET1	ET2	CT	CT1	CT2	TD	TD1	TD2	EE	EE1	EE2
Transformation	2.2	3	4.3	0.2	0.7	1.2	- 0.6	- 0.7	- 0.8	-1.1	-1.4	-1.5
Resources	- 1.7	- 2.2	- 3.1	- 0.2	- 0.7	- 1.1	- 2	- 2.4	- 2.7	-3.5	-4	-4.5
Emission cost				0.3	1	1.5						
NPV	0.5	0.8	1.2	0.3	1	1.6	- 2.7	- 3	- 3.6	-4.6	-5.4	-6

It is observed from Table 6-3 that the cumulative costs of implementing the emission targets and carbon tax scenarios are 0.5 to 1.2 billion US$ and 0.3 to 1.6 billion US$ respectively, compared to the OPT scenario. This is largely due to the higher capital investment (transformation cost) of RET, which are deployed in much higher capacities. Even though, the constraint on the optimum generation system resulted in savings in the use of resources, these savings were not sufficient to offset the high capital investment.

The introduction of policies to improve transmission and distribution losses to levels proposed in this section will lead to 2.7 to 3.6 billion US$ cumulative cost savings over the study period. This significant cost savings is due to the reduction in generation requirement (Figure 6-9). It should be noted that financial cost in the implementation of measures to reduce transmission and distribution losses were not quantified in this study. This is mainly due to unavailability of reliable information on the topic in Ghana. However, the high savings suggest the need for the country to adopt strategies to reduce these losses. Greater value should be placed on reducing the non-technical losses, which constitute the bulk of the transmission and distribution losses in Ghana [3]. According to [146], only 50% of the electricity generated in sub-Sahara Africa is paid for. This is attributed to a combination of low percentage of billing electricity injected in distribution networks and low collection of billed amounts. The country should therefore consider the implementation of Advanced metering infrastructure (AMI) for monitoring consumers, the use of temper proof meters and replacement of old meters with accurate electronic meters and frequent energy audits up to the distribution transformer [147]. These measures have proven to be very effective in reducing non-technical losses in North Delhi from 53% in 2002 to 15% in 2009 [147].

The Government of Ghana currently subsidies fuel to make electricity affordable. However, the sensitivity analyses show that phasing these subsidies will gradually make NRET economically attractive. There should however be gradual [147] and should be linked to expansion in NRET.

6.4 ENVIRONMENTAL ANALYSIS

The LEAP model contains GHG emission factors, required for environmental assessment. The AR4 factors were applied in this study in line with IPCC recommendations [135]. Table 6-4 shows cumulative GHG emissions at points of emissions from the various scenarios.

Table 6-4 Cumulative emissions and cost of avoided CO_2 emissions

Scenario	Cumulative emission (Mt CO_2e)	CO_2e savings (%)	Cost of avoiding GHG ($/tonne CO_2e)
OPT	223		
ET	187	16	13.9
ET1	170	24	15.1
ET2	141	37	14.4
CT	217	3	53.8
CT1	202	9	48.1
CT2	190	15	48.5
TD	168	25	- 48.3
TD1	160	28	- 49.3
TD2	150	33	- 49.1
EE	123	45	-45.7
EE1	107	52	-46.5
EE2	92	59	-45.9

Table 6-4 confirms the mitigation potential of the policies evaluated in this study. Significant GHG emission reduction potential of 16% to 37% is achieved with the introduction of CO_2 emission targets. This is because of the relatively higher share renewable generation. The emission targets compelled higher deployment of renewable energy technologies, since they emit low to zero emissions.

Table 6-4 further reveals that introduction of carbon tax at levels proposed in this study will not yield significant GHG emission savings. The cumulative GHG emission savings in the high carbon tax scenario (CT2) compared to OPT scenario was 15%, while that of ET2 and TD2 scenarios were 37% and 33% respectively. These results show that even though costing emissions will increase the operational cost of thermal generation, it does not automatically lead to adoption of renewable energy technologies. There is a tendency by utility providers to transfer this extra cost to consumers. This negative impact of carbon tax can be addressed with the investment of tax revenue in the development of renewable technologies.

The cost effectiveness of GHG emission was analysed by calculating the cost of avoiding CO_2 emission. Cost of CO_2 avoided is the cost of reducing CO_2 emission to the atmosphere expressed as $/tonne of CO_2 not emitted with respect to the base case scenario. The decision criterion is to identify the least cost alternative in reducing a tonne of CO_2. The results show superior performance of the transmission and distribution and the energy efficiency scenarios in achieving economically efficient CO_2 emission reduction. While all the other policy scenarios resulted in abatement cost, the transmission and distribution, and energy efficiency scenarios resulted in benefits. This is because of their relatively lower demand achieved with the implementation of transmission and distribution, and efficiency strategies. The country can therefore benefit immensely from the global market with the implementation of appropriate energy policies.

The analyses suggest that significant economic and environmental benefits are achieved with the implementation of energy efficiency and improvements in transmission and distribution losses in Ghana. This means that if the Government of Ghana intends to achieve reduction in demand and greenhouse emission, strategies to improve demand side efficiency should be pursued. Demand side management strategies such as energy standards for refrigeration and air conditioners, and phasing out of incandescent bulbs have been implemented in countries such as UK, India, china, USA and Canada with high degree of success [116].

The country should also implement policies to promote the reduction of both technical and non-technical T&D losses. Conventional approaches for improving technical losses with higher benefit/cost that can be pursued to reduce these losses are discussed in [147]. Seventy percent (70%) of the transmission and distribution losses in Ghana in 2014 were due to non-technical losses mainly through electrical theft and meter tempering and non-payment of bills. Installation of heavy-duty locking rings and the use of prepay meters can help improve non-technical losses [146].

Ghana being a signatory to the UNFCCC has an obligation to report periodically on measures taken to reduce greenhouse gases. The analysis of the possible least cost generation pathways show that further reduction in GHG is possible in Ghana with the implementation of additional policies. These measures when fully implemented will lead to sustainable low-carbon development of the generation system.

6.5 SUMMARY

In this Chapter, LEAP/ OSeMOSYS optimisation tool was applied to determine the optimum development of the country's generation system up to 2040. The developed system was applied to the case study of the reference scenario (OPT) which examines the least cost development of the system without any shift in policy.

Four groups of policy scenario were developed based on the future possible energy policy direction in Ghana: energy emission targets, carbon taxes, transmission and distribution losses improvements and demand side efficiency. The model was then used to simulate the development of technologies in each scenario up to 2040 and the level of renewable generation examined. Finally, cost benefit analysis of the policy scenarios, as well as their greenhouse gas mitigation potential were also discussed.

The results show that: suitable policies for clean power generation have an important role in CO_2 mitigation in Ghana. The introduction of carbon minimisation policies will also promote diversification of the generation mix with higher penetration of renewable energy technologies, thus reducing the overall fossil fuel generation in Ghana. It further indicated that, significant greenhouse emissions savings is achieved with improvement in transmission and distribution losses, and demand side efficiency.

CHAPTER 7

POLICY PERSPECTIVE FOR FUTURE GENERATION SYSTEM OF GHANA

The analysis in the previous chapter shows that the energy efficiency scenario is the most promising scenario to achieve reduction in GHG, increase RE generation share and lower overall system demand. Higher deployment of RET in the alternative scenarios also resulted in overall benefits compared to the reference scenario. Energy efficiency strategies and renewable energy generation should therefore form the core of future energy policy in Ghana. This chapter examines policy options for promoting EE and RE development. The chapter then reviewed existing energy policies in Ghana to identify improvement that could lead to high integration of RET and improve energy efficiency.

7.1 Enabling Factors Supporting RE and EE Deployment

An enabling environment characterised by sound appropriate policies is necessary for the deployment of RE and EE strategies. The role of appropriate institutional policies and strategies in the development of sustainable energy technologies cannot be over emphasised [1, 148]. A well-prepared policy framework will not be successful without the necessary support mechanisms. These enablers can be categorised as follows [148]:

- Institutional and regulatory factors
- Financial and economic factors
- Technical, infrastructure and innovative factors

- Social factors
- Environmental factors

A brief overview of these categories is illustrated in Figure 7-1 [148].

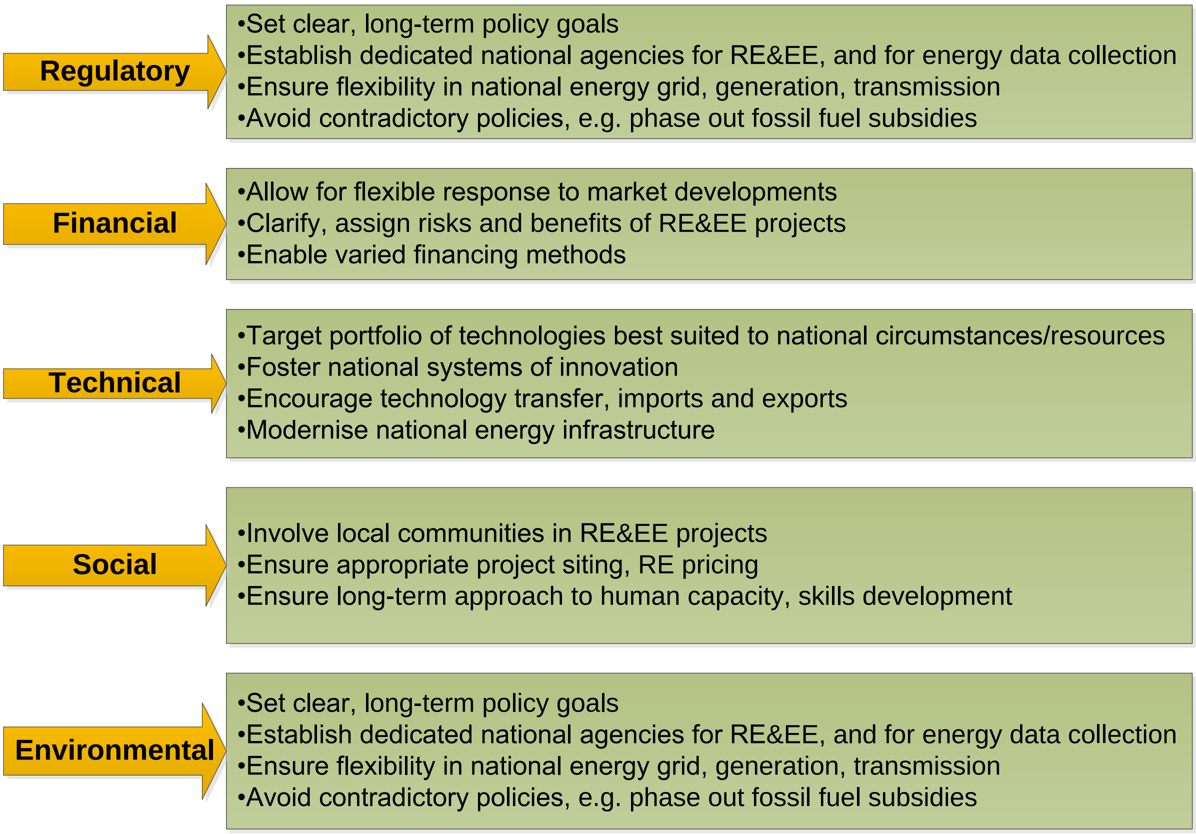

Figure 7-1 Overview of enabling factors for RE&EE deployment [148]

Economic instruments focus on improving the relative competitiveness of RET making use of direct investments in infrastructure; financial incentives such as feed-in-tariffs, grants and subsidies, loans as well as tax relieves; and market based instruments such as GHG emissions allowances, green and white certificates. Information and education policies include target awareness building, professional training and qualification as well as capacity building. This could be in the form of artisan training; where installers are trained, and certificated to meet the technical requirements of a technology. Policy support provides a legal framework for the implementation of RET. It takes the form of strategic energy planning and institutional creation. The research and development policy involves the establishment of demonstration projects as well as providing policies to encourage industrial support for research programmes in RET.

7.1.1 Policy Options for Supporting RE Development

The analyses of the scenarios in Chapter 5 and Chapter 6 show that RE systems will play an important role in future generation system in Ghana. Their deployment will however depend to a large extend on the policy and institutional framework. This is because policies and regulations play an important role for creating enabling environment for renewable systems. Backed by clear and reliable targets, comprehensive scenarios should be designed to meet the following criteria [148]:

- Provide adequate remuneration for RE generation
- Guarantee revenue and facilitate access to debt and equity capital markets. These can be achieved through sustainable long-term power purchase agreements.
- Allow effective grid integration
- Remove non-economic barriers

Figure 7-2 provides a summary of policies for promoting RE deployment. [148].

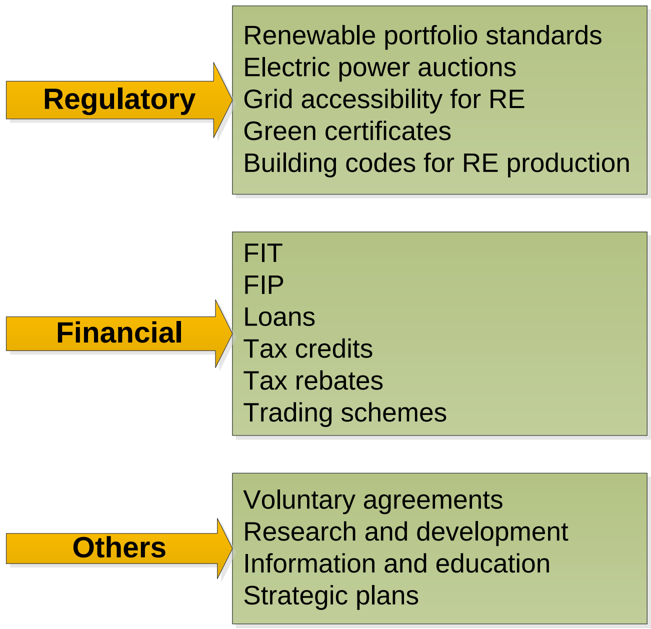

Figure 7-2 policies for RE deployment [149]

RE targets with short to long-term deployment targets provide confidence to stakeholders of the desire of the country to pursue RE development. In 2014, about 144 countries have reasonable targets in place. The Government of Ghana has set a target in 2006, to achieve 10% RE generation by 2020 [4].

The common financial policy mechanisms include feed-in tariffs (FIT), feed-in premiums (FIP), renewable portfolio standards and trading systems. FIT, which is the most widely used mechanism has been adopted in Ghana. FIT provides guarantee price for RE over a period. FIP, which are currently been adopted by many countries in the European Union, provide additional revenue by paying investor according to electricity generated or installed capacity [148].

Many policy types and strategies have already been developed to promote the development and utilization of RET. Table 7-1 provides a summary of the various policy types currently in operation in Ghana adopted from [150].

Table 7-1 Key elements of RE policies and strategies in Ghana [150]

Title	Effective	Policy type	Objectives / Key features
Net metering code	2015 Planned	Regulatory, Economic	Provision of guidelines for connection net metered RE to distribution system
Feed-in tariff	2013 (amended 2014)	Economic	Setting up of rates for purchase of electricity from RE Ensure sustainable development and integration of RE into national energy mix
Renewable energy act	2011	Policy support	Framework to support development Creating enabling environment to attract investment in RE. Promote the use of RE
Ghana national energy policy	2010	Policy support	Setting up of rates for purchase of electricity from RE Ensure sustainable development and integration of RE into national energy mix
National electrification scheme	2007-2020	Research development Economic i	Facilitate the entry of independent power producers Promote exploitation of RE through the creation of favourable regulation and pricing incentives Provision of tax incentives for RE equipment Encourage research to reduce cost of RE technologies
Ghana energy development and access project (GEDAP)	2007	Economic	Overall power sector development Renewable energy development
Strategic national energy plan (SNEP)	2006-2020	Policy support	10% NCRE[11] share of installed capacity by 2020 Achieve 100% universal electrification by 2020 Achieve 30% rural electrification by via RET by 2020 Recommendation for establishment of technical regulations for RE system as well as setting favourable feed in tariffs
Renewable energy services programme (RESPRO)	1999	Economic	Manage and extend solar PV services to rural communities

The renewable energy act of Ghana [38] provides the legal backing for the development, management and utilization of RE for power generation and other related issues. The main highlights of the policy on the requirement for electricity generation include:

[11] This excludes the conventional large hydro generation

- The establishment of feed in tariff scheme to guarantee the sale of power from renewable resources. The rate will be determined with the guidance of the Public Utility Regulatory Commission of Ghana.
- The RE purchase obligation, which makes it mandatory for electricity distribution utility or a bulk consumer to purchase a specified percentage from RE sources.
- The establishment of a renewable energy fund. The objective of the fund is to provide financial incentives for the development of these systems.

The feed-in system is in place in Ghana but has not had an impact in the expansion of RE systems. The current feed-in-tariff for the various renewable technologies in the Ghana is presented in Table 7-2.

Table 7-2 Feed in tariff of Ghana [151]

Technology	Rate (US cent/kWh)
Solar PV with grid stability/storage systems	20.1378
Solar PV without grid stability/storage systems	18.2470
Wind with grid stability systems	17.4259
Wind without grid stability systems	16.0805
Hydro ≤ 10MW	16.7648
Hydro (10MW > ≤ 100MW)	16.8480
Biomass	17.5106
Biomass (enhanced technology)	18.4571
Biomass (plantation as feed stock)	19.7871

These tariffs expressed in Ghana pesewas are based on an exchange rate of GH₵3.1985 to US$1.000 (September 2014) and will be reviewed every two years by the public utility regulatory commission [30].

It was observed from Table 7-1 that there has been a consistent effort to improve the institutional arrangement aimed at encouraging the high deployment of clean energy technologies. However, the current appraisal of the installed capacities of NRET systems seems to suggest that some of the policies targets set up are behind schedule. The SNEP for instance, had projected 10% NRET share of generation by 2020. The current (2014) RE generation share of less than 0.001% [3] clearly show this target will most likely not be achieved. This target year has subsequently been revised to 2030 [133].

The slow deployment of NRET in the country despite favourable policies is attributed to many barriers. These barriers affect can be classified under the following groups: market, Economic and financial, human capacity, technical, regulatory framework and social barriers. The specific barriers under each category are list below.

1. **Market barriers** - Size of the market for RE systems, Controlled market in favour of conventional systems, failed experience, lack of successful reference projects.
2. **Economic and financial barriers -** Access to finance and long-term capital, Lack of consumer financing options, Business climate (Currency fluctuation), insufficient incentives.
3. **Human capacity** - Technical skills to operate and maintain RET, Project development skills, Lack of adequate training centres.
4. **Technical barrier** - Poor operation and maintenance facilities, difficulty in getting spare parts, equipment.
5. **Regulatory barrier** - Inadequate standards and codes, Lack of enforcement, Challenges with license acquisition
6. **Social barriers** - Lack of understanding of local needs, Public acceptance of RET.

Nine of these barriers were identified by [152] through a survey conducted with stakeholders of the renewable energy industry in Ghana. Table 7-3 presents the key barriers and proposed mitigation measures.

Table 7-3 mitigation actions for removing key barriers to RET development [152]

Category	Key barriers	Mitigation action
political	Lack of enforcement and political will	Expedite the development of RE master plan Operationalize the RE fund and RE law Develop national programmes on prioritized RET Develop/adopt standards, codes and labels for biogas plants, solar dryers, wind mills and other RET
Economic	High initial cost High interest rate Unstable currency Limited access to capital	Develop and implement tax incentives on prioritized RET Provide financial support for RET investment in prioritized sectors
Technical	Inadequate training facilities Lack of skill personnel for manufacturing	Strengthen existing training facilities Build capacity of researchers and trainers in RET Conduct capacity building programmes for entrepreneurs and local enterprises
Socio-cultural	Poor or lack of information about cost and benefits of RET	Run cost-benefit campaign on the use of RE products Include RET in technology catalogue

The mitigation actions presented in Table 7-3 should therefore form the core of future policy aim at RET development

7.1.2 Policy Options for Supporting EE Development

Energy efficiency offers a cost-effective way of achieving sustainable energy future. Improvements in efficiency have benefits that affect the various sectors of the economy. Efficiency leads to reduction in domestic energy demand. This enables poor households to be able to acquire more and better energy services. The utility company can also provide more household with electricity. This will lead to improve health and well-being of consumers with improved energy supply. Efficiency also reduced energy bills and increased disposable income for consumers. At the national level, energy efficiency can lead to reduction in energy related expenditure. This includes the reduction in cost of fuel and energy infrastructure. Improvement in efficiency will also have positive macroeconomic impact including increases in GDP. At the international level, energy efficiency would lead to direct GHG emission reduction. This makes EE to be at the core of many climate change mitigation strategies [153].

These advantages make the implementation of EE policies very important for long-term sustainable energy development. Proven mechanism applied to the various sectors of demand are summarised in Figure 7-3.

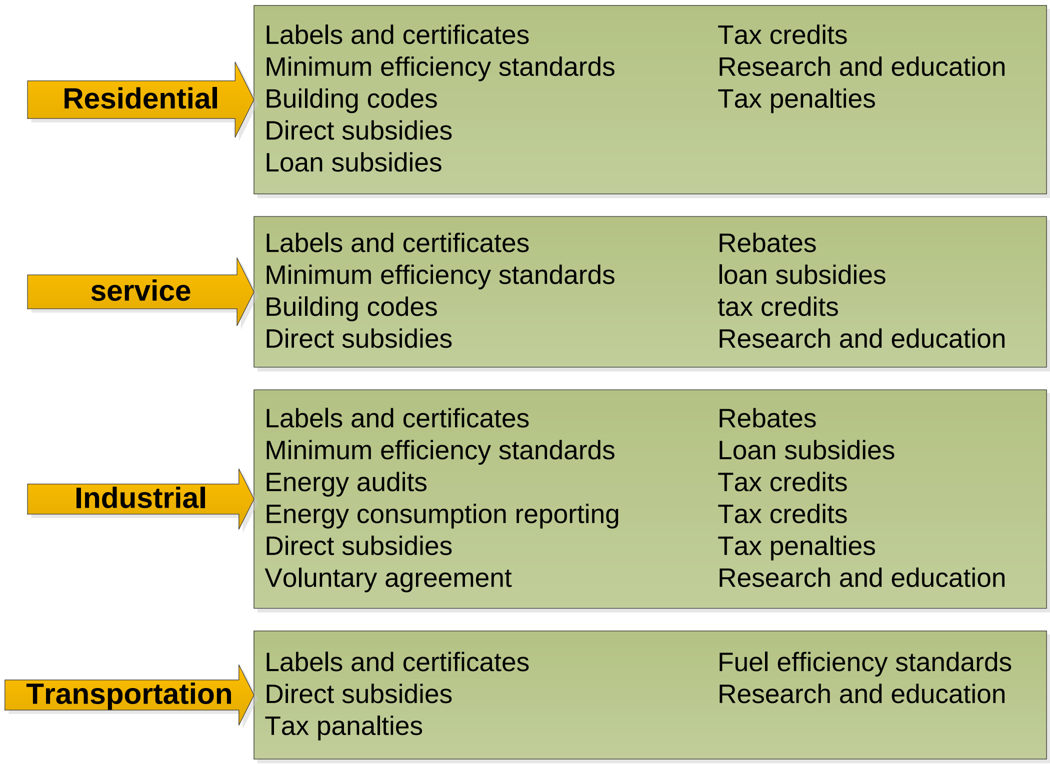

Figure 7-3 Energy efficiency policy mechanisms for demand sectors [149]

It is observed from Figure 7-3 that some of the policies options are applied to all the sectors. These include labels and certificates, rebates, research, development and education and direct subsidies. Some measures are designed for specific sectors such as fuel efficiency for transport and building codes for domestic and commercial buildings. It is however common to implement measures simultaneously to complement each other [149].

Ghana has recently adopted many strategies to improve efficiency in the demand side. Notable among them is the replacement of filament bulbs with Compact Fluorescent Lamps (CFL) and the refrigeration efficiency schemes. The CFL replacement scheme increased the CFL penetration between 2007 and 2009 from 3% to 79% resulting in an annual energy savings potential of 6.75% of total electricity consumption [17]. A survey by the energy commission of Ghana [15] shows that the average annual energy consumption of refrigerators in Ghana is 1200 kWh. The efficiency standard as part of the refrigeration replacement scheme limits this to 650 kWh/annum. This will thus result in an energy saving potential of about 46% [15].

The current energy efficiency strategies however concentrate on improving domestic consumption. There is still an “efficiency gap” in industrial and other sectors. Ghana industrial energy intensity survey shows the energy intensity for steel production in the country to be 807 kWh/tonne compared to 550 KWh/tonne in India, 450 kWh/tonne in USA and 380 kWh/tonne in Japan as well as Germany [15].

There is therefore the need to develop a national EE with specific targets for all demand sectors. Table 7-4 provide a summary of targeted areas that could be adopted by Ghana as part of its medium to long term energy efficiency strategies.

Table 7-4 Suggested priority areas for energy efficiency policies in Ghana [148]

Sector	Action
All sectors	Ensure well-equipped institutional mechanisms for collating national efficiency data
	Established and Resource an independent agency solely for energy efficiency, to focus on timely and effective policy implementation
	Promote funding and incentive mechanisms
	Raise public awareness on the gains of EE
Lighting and appliances	Established and enforce appliance labelling system
	Establish minimum energy performance standards (MEPS) for major energy consuming appliances
Buildings	Develop and implement building codes
	Provide detailed timeline for improving efficiency of existing buildings
Industry	Introduce mandatory energy audits
	Require MEPS for industrial equipment

7.2 Policy recommendation for future generation development in Ghana

This section provides a summary of policy direction for future generation system of Ghana based on the results of the alternative and least cost generation scenarios analysed in the study.

Improvement in demand side efficiency should be vigorously pursued. Efficiency measures that currently focused on residential consumers should be expanded to include the commercial and industrial sectors. The domestic measures should include the phasing out of incandescent bulbs and enforcement of energy efficiency labelling for electrical and electronic equipment especially refrigerators and air conditioners. Industrial measures should include mandatory audits and MEPS (Table 7-4)

Secondly, the country should implement strategies to reduce transmission and distribution losses. The country should consider implementing policies to promote the reduction of both technical and non-technical T&D losses.

Credit incentives such as investment tax credits and low cost loans should be provided to promote domestic use of RET. Tax breaks and other incentives should be provided for utility scale renewable energy systems.

There is also the need to introduce GHG emission tax. Such a tax will not only lead to awareness of the effect of these emissions but will also provide a more balanced economic appraisal of the different generation options. Funds realized from this tax could be used to set up special fund to aid renewable energy development.

Imposition of emission targets directly affects the development of RET. The country should therefore impose specific targets with timelines. Enforcement of emission targets in the country will encourage the exploration of alternative energy sources by the country utility companies.

Finally, policy evaluation should be undertaken to ascertain the impact of existing policy on the country generation system. This will lead to the identification of the lapses of these policies and the development of a uniform framework to promote the future development of the system.

7.3 SUMMARY

This section explored the various policies and interventions for promoting RE and EE deployment. The chapter also analysed the various energy policies and the barriers to RE development in Ghana. The section identified barriers and explored options to promote the deployment of RE and EE activities in Ghana. It emerged from the study that in Ghana many barriers relate to the implementation. Implementation phase barriers include lack of clear policy and capacity to regulate. The other barriers relate to lack of finance, inability to operate and maintain RE and EE equipment after installation, as well as weak capacity undertake EE projects.

There is therefore the need for capacity building and establishment of dedicated government agency solely for renewable energy development. This will go a long way to streamline the various policies, create public awareness and facilitate the development of the vast renewable energy resources in the country. Such an agency will also lead to the development of a long-term generation plan taking into consideration all the available energy resources in the country. It is believed that proper implementation of this policy will encourage investment in the huge renewable energy potential that will meet the energy needs of the country.

CHAPTER 8

SUMMARY, CONCLUSION AND RECOMMENDATIONS

This chapter presents the concluding summary and recommendations for the research. The aim of this chapter is to summarise the findings of the research and make recommendations for further works.

8.1 SUMMARY

The main objective of this study was to provide a comprehensive analysis of electricity generation expansion planning in Ghana power system. To achieve this objective, the LEAP tool was adapted to the specific energy situation in the country. The developed Ghana LEAP was used to analyse the generation system in order to determine the mix and amounts of different generation technologies based on their availability.

The need for long-term electricity planning in Ghana was established by a comprehensive review of the country's power system. The review discussed the problem Ghana faces in the supply of electricity to various industries and households in both urban and rural areas that adversely affect the quality of life in general.

A further review was undertaken to explore the various methodologies employed in scenario analysis, energy planning tools and literature that applied the LEAP tool. The review on scenario methodologies provided the basis for developing the scenario framework for this study. The adapted methodology incorporated the advantages of both qualitative and quantitative approaches. The review on energy planning models further provided a justification for the selection of the LEAP tool. This review also provided data and provided direction to this study.

The second objective was to develop a model of the power system of Ghana. The Ghana LEAP model was developed by analysing electricity demand drivers and extrapolation of input variables. The performance of the generation system of Ghana in year 2010 was used to develop the reference system. This reference system, which shows the fuel mix, used, the electricity flow and technologies parameters is the foundation for the development of Ghana LEAP.

The assessment of future development of the generation system requires a projection of future demand up to 2040. The demand forecast was performed using key input parameters including Gross Domestic Product (GDP), population change and urbanisation. The bottom-up methodology was adopted for the demand forecast.

The growth of the Ghana power system was examined by developing four scenarios based on key variables that could potentially affect the future development of the power. The four scenarios include Base case, Coal, Modest RET and High RET scenarios.

The least cost development of the generation system of Ghana was developed using the optimisation approach in LEAP. Optimisation can be seen as the simulation of the electricity supply in an ideal environment. This approach therefore, does not necessarily reflect the actual power market environment. However, it provides policy makers with a picture of the system when all generation options were given equal consideration. The study examines the optimum development of the generation system without any policy constraints. The outlook of the optimum system with imposition of carbon tax, improvement of transmission and distribution losses, emission targets and demand side efficiency was analysed.

The review further incorporated an assessment of the energy policies for Ghana. It revealed that the current policies are short-term focused, internally inconsistent and fragmented. Thus making their implementation and assessment difficult. Consequently, they do not address the eminent long-term energy challenges in the country. The country is therefore yet to benefit from the abundant renewable energy resources, particularly solar.

8.2 CONCLUSION

The overall results of this study suggest the competitiveness of NRET in all simulations and sensitivities. The cost of RET has declined and advances in technology is expected to lead to further reduction. In Ghana, due to the current shortage in supply, the country has focussed in solving its immediate energy needs by providing incentives to electricity suppliers that can supply firm generation to meet the deficit. These incentives favour fossil fuel power plants and explain why the current expansion trend is mainly by thermal plants.

The results also provide an overall picture of the RET potential in Ghana. The development of the energy technologies in the scenarios demonstrated the extent to which RET could be integrated into the generation system of Ghana and the benefits of their high integration. The results show that significant GHG emissions savings of up to 40% was achieved in the High RET scenario resulting in net benefits in cost of avoided GHG emissions. This study therefore concludes that Ghana could benefit from carbon trading under Kyoto protocol, if the country could develop its generation system with high deployment of RET, additional benefits in the form of carbon trading under the Kyoto Protocol could be achieved. This will have significant implications for further development of renewables with availability of funds, which is the main obstacle for the implementation of these technologies.

Furthermore, the degree of diversification of the energy system was increased in all alternative scenarios. The energy supply system would diversify from a system dominated by thermal and large hydro plants to a system that included a greater use of NRET. Diversification of the generation mix has reduced the overall fossil fuel generation, which is characterised by unreliable feedstock fuel supply as well as price shocks. This could improve the energy security of the country.

The least cost development of the generation system showed that wind and small hydro provided the overall least cost generation among the NRET. These technologies could be introduced much earlier on their own merit (Chapter 6). For fossil fuel plants, natural gas was identified as the least cost as well as lowest GHG emitting plant. Thus, the best system for long-term generation should explore the high renewable potential to supplement natural based thermal generation.

In conclusion, this study proposed promoting energy efficiency in both demand and transmission, and the utilisation of renewable energy as the best energy strategies for Ghana. Improvement in energy efficiency has reduced the need for investment in energy infrastructure. The currently (2014) developed renewable energy capacity contributes 0.01% of grid electricity generation. The Government planned to increase renewable generation share to 10% by 2030 [133]. This thesis suggests 30% by 2030 and is a target that can be meet using appropriate mechanisms to harness the abundant renewable potential of the country. The study therefore recommends the implementation of strategies to reduce transmission and distribution losses and improve demand efficiency. This will promote the development of more efficient, reliable and environmentally acceptable energy system in Ghana.

8.3 RECOMMENDATIONS

Data availability was a critical problem in the study. There is no systematic data collecting mechanism in Ghana. Data used for this study was therefore collected from various secondary sources including Energy commission, GRIDCO, VRA and from national and international publications. The study recommends further studies to address the unavailability of sufficient data. Further research should be conducted to fully ascertain the biomass and MSW resources in the country. The use of solid residue from timber and agriculture, domestic and industrial liquid waste, their collection, transport and disposal should be further assessed. These technologies unlike PV and wind are not intermittent and can therefore contribute to firm generation.

Power plants with the same input and output were modelled in LEAP as single technologies without considering geographical characteristics and other specific plant characteristics. The location of a power plant is particularly important to aid in transmission and distribution investment and stability. The model could therefore be improved with disaggregation of the power generation making used of their actual operating characteristics.

Transmission and distribution cost, land use and potential cost of affecting local livelihoods were not considered in this study. This was not only due to lack of reliable data, but also on the scope of this study, which focuses on how the various supply and demand side constraints will influence the development of generation options.

LEAP does not have the capability to assess the effect of high penetration of RET on grid stability. This was therefore not considered in this thesis. Further studies need to be carried out to assess the impact of high penetration of renewable RET on the stability of the grid as well as grid expansion studies to accommodate the potential future generation expansion.

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APPENDICES

Appendix A Overview of commonly used energy planning tools [119]

Cities for Climate Protection Software (CCP)

CCP is a software tool designed primarily to help members of ICLEI's (International Council for Local Environmental Initiatives) Cities for Climate Protection Campaign develop their local climate action plans. The software can be used to develop greenhouse gas emissions inventories for cities based on their energy use and waste generation. It can also be used to help quantify financial savings, air pollutant reductions and other co-benefits of greenhouse gas emission reduction strategies. www.torriesmith.com

COMPOSE

COMPOSE (Compare Options for Sustainable Energy) is a software tool for energy systems analysis. COMPOSE may be used for design and cost-effectiveness analysis of energy projects, comparing local and system-wide energy, environmental, and economic consequences. It can also be used to compare projects of differing nature and lengths, enabling prioritization among a range of alternatives. COMPOSE is also designed to act as a social platform for sharing and comparing case studies and solutions. www.energianalyse.dk

HOMER

HOMER (hybrid optimisation of multiple energy resources) simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation (DG) applications. HOMER's optimization and sensitivity analysis algorithms can be used to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. HOMER models a wide range of conventional and renewable energy technologies. Power sources that can be modeled include: solar photovoltaics (PV), wind turbines, run-of-river hydro power, diesel, gasoline, biogas, alternative, co-fired and custom-fueled generators, electric utility grids, microturbines, and fuel cells. Storage options include: battery banks and hydrogen. www.homerenergy.com

MESSAGE

MESSAGE is used to formulate and evaluate alternative energy supply strategies under different user defined and physical constraints. Examples include: new investment limits, market penetration rates for new technologies, fuel availability and trade, environmental emissions, etc. MESSAGE is extremely flexible and can also be used to analyze energy/electricity markets and climate change issues. It belongs to the same family of models as MARKAL, EFOM and TIMES and relies on a technology rich description of the energy system. It chooses the most cost effective arrangement of technologies and energy carrier use to meet the demands for energy service specified. Unlike many other optimization models, it does not require purchases of GAMS, nor a commercial solver. A free Linear Programming (LP) solver is provided. However depending on the problem complexity more powerful LP and Non-Linear Programming (NLP) solvers, such as CPLEX, can be seamlessly used by the software. www.iaea.org

REAP

REAP provides baseline data and scenario modelling of carbon, greenhouse gas and ecological footprints for the regions and local authorities of the UK. The tool currently provides the following functions (for all local authorities and regions in the UK):

- Footprint data by production sector
- Footprint by household consumption category
- Time series emissions data from 1992-2004 by region
- A comparison tool to compare data across geographies
- A composite region function to join local authorities or regions
- Update data function where baseline data can be changed
- Future scenario creation and analysis
- Evaluation of scenarios and results display

The scenario functions in REAP enable a policy maker to answer "What If" questions about the effects of policy on the environment helping to formulate strategies for local, regional and national government. Scenarios can be created across all areas of consumption, allowing the user to see the effects of changes to consumption, such as energy demand, travel or food, on the footprint in the local area over time. Changes to population and other consumable goods and services can also be incorporated, along with changes to the efficiencies of different production sectors over time. All of these areas of consumption can be changed individually or as a group, allowing scenarios to be as simple or complex as required. www.resource-accounting.org.uk/reap

RETSCREEN

RETScreen International Clean Energy Project Analysis Software can be used world-wide to evaluate the energy production, life-cycle costs and greenhouse gas emission reductions for various types of energy efficient and renewable energy technologies (RETs). The software also includes product, cost and weather databases, and a detailed online user manual. The RETScreen International Online Product Database provides users access to contact information for more than 1,000 clean energy technology manufacturers around the globe, including direct Website and Internet links from within the RETScreen software and from this Website (Marketplace). In addition, the database provides access to pertinent product performance and specifications data for a number of these manufacturers. These data can be "pasted" to the relevant cells within the RETScreen software. The RETScreen software currently includes modules for evaluating: wind energy, small hydro, solar photovoltaics (PVs), combined heat and power, biomass heating, solar air heating, solar water heating, passive solar heating, ground-source heat pumps, and refrigeration.

www.retscreen.net

TIMES/MARKAL

MARKAL (Market Allocation) is a technology-rich energy/economic/environmental model. It was developed in a collaborative effort under the auspices of the IEA's Energy Technology Systems Analysis Programme (ETSAP). MARKAL is a generic model tailored by the input data to represent the evolution over a period of usually 20 to 50 years of a specific energy-environment system at the national, regional, state or province, or community level. The system is represented as a network, depicting all possible flows of energy from resource extraction, through energy transformation and end-use devices, to demand for useful energy services. Each link in the network is characterized by a set of technical coefficients (e.g., capacity, efficiency), environmental emission coefficients (e.g., CO2, SOx, NOx), and economic coefficients (e.g., capital costs, date of commercialization). Many such energy networks or Reference Energy Systems (RES) are feasible for each time period. MARKAL finds the best RES for each time period by selecting the set of options that minimizes total system cost over the entire planning horizon. TIMES (The Integrated MARKAL-EFOM System) builds on the best features of MARKAL and the Energy Flow Optimization Model (EFOM). In order to work with MARKAL, you need a number of software elements: MARKAL itself, a user-interface (two are available for Windows: ANSWER and VEDA), GAMS (a high-level modeling system for mathematical programming problems) and an optimizing solver such as MINOS, CPLEX or OSL. A number of varations of MARKAL are available including

- MARKAL-MACRO: which links MARKAL with a macroeconomic model to provide demands that are endogenous and responsive to price, and estimates of GDP impact and feedbacks.
- STOCHASTIC, which associates probabilities with the occurrence of each scenario, allowing hedging strategies to be determined that identify robust rather than purely optimal strategies.
- GOAL PROGRAMMING: which solves MARKAL according to the weighted preferences of various stakeholders with respect to cost versus environmental goals. www.iea-etsap.org

TRACE

The Tool for Rapid Assessment of City Energy (TRACE) is a decision-support tool designed to help cities quickly identify under-performing sectors, evaluate improvement and cost-saving potential, and prioritize sectors and actions for energy efficiency (EE) intervention. It covers six municipal sectors: passenger transport, municipal buildings, water and wastewater, public lighting, solid waste, and power and heat. TRACE consists of three modules: an energy-benchmarking module which compares key performance indicators among peer cities, a sector prioritization module which identifies sectors that offer the greatest potential with respect to energy-cost savings, and an intervention selection module which functions like a "playbook" of tried-and-tested EE measures and helps select locally appropriate EE interventions. www.esmap.org/TRACE

WEAP

Freshwater management challenges are increasingly common. Allocation of limited water resources between agricultural, municipal and environmental uses now requires the full integration of supply, demand, water quality and ecological considerations. WEAP, the Water Evaluation And Planning system is a user-friendly software tool that incorporates these issues into a practical yet robust tool for integrated water resources planning. It provides a comprehensive, flexible and user-friendly framework for planning and policy analysis. WEAP also be used in conjunction with LEAP for energy-water nexus analyses. www.weap21.org

EnergyPlan

EnergyPLAN is a user-friendly tool designed in a series of tab sheets and programmed in Delphi Pascal. The main purpose of the tool is to assist the design of national or regional energy planning strategies by simulating the entire energy-system: this includes heat and electricity supplies as well as the transport and industrial sectors. EnergyPLAN can model all thermal, renewable, storage/conversion, transport, and costs (with the option of additional costs). It is a deterministic input/output tool and general inputs are demands, renewable energy sources, energy station capacities, costs, and a number of different regulation strategies for import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity. In the programming, any procedures, which would increase the calculation time, have been avoided, and the computation of 1 year requires only a few seconds on a normal computer. Finally, EnergyPLAN optimises the operation of a given system as opposed to tools which optimise investments in the system.

Appendix B Results of National Energy survey by EC in 2010 [3]

Average Monthly Fuel Consumption per Household

Location	Firewood (kg)	Charcoal (kg)	LPG (kg)	Kerosene (l)	Electricity (kWh)
Urban	82.2	35.9	14.5	1.5	100
Rural	92.8	36.7	4.8	4.5	73.3
Coastal	84.3	33.8	9.7	3.9	97.
Forest	90.4	37.0	9.0	3.4	83
Savannah	97.1	37.1	7.3	3.3	56.2
National	88.7	36.2	7.3	3.5	100

Average Monthly Electricity Consumption by Electrical Appliances per Household (kWh)

Location	Refrigeration	Lighting	Television	Fan	Iron	Others
Urban	73.1	21.8	12.2	12.2	4.8	5.5
Rural	102.3	21.8	10.7	10.7	4.6	3.7
Coastal	99.8	29.4	9.7	10.7	4.3	5.0
Forest	76.1	20	8.5	11.8	4.2	3.0
Savannah	102.3	20.6	10.7	9.1	5.5	3.7
national	77	21.8	12.2	11	4.9	4.6

Appendix C Official aggregate peak demand projections for Ghana

EC projection from 2006 to 2020 (MW)

Year	Low growth	Moderate	High growth
2006	1132.8	1209	1451.8
2007	1313.3	1407.3	1616.9
2008	1381.1	1494.9	1749.7
2009	1456.2	1591.6	1898.4
2010	1532.2	1691.4	2050.8
2011	1601.3	1786.7	2206.5
2012	1674.5	1888.5	2377.8
2013	1741.4	1986.7	2555.9
2014	1812.1	2091.8	2752.8
2015	1886.8	2199.2	2963.6
2016	1965.8	2313.7	3197.5
2017	2049.4	2435.9	3457.6
2018	2137.8	2566.3	3738.3
2019	2231.2	2705.3	4044.7
2020	2330.1	2853.7	4387.8

GRIDCO projection from 2012 to 2026 (MW)

Year	2012	2018	2020	2023	2026
Low	1626	1937	2365	2643	2960
Base	1857	2309	3046	3552	4161
high	1991	2718	3848	4680	5733

Appendix D detail plant operational characteristic from 2010 to 2014 [3, 15, 16, 130]

Generation Capacity as of December 2010

Plant	Fuel	Owner	Capacity (MW)				Generation	
			Install	%	Dependable	Available	GWh	%
Akosombo hydro	Hydro	VRA	1020		960	960	5961	
Kpong hydro	Hydro	VRA	160		140	140	1035	
Total hydro			**1180**	**54**	**1100**	**1040**	**6996**	**69**
TAPCO	Oil/NG	VRA	330		300	200	1234	
TICO	Oil/NG	VRA	220		200	200	1160	
Tema thermal 1	Oil/NG	VRA	126		100	80	591	
Tema thermal 2	NG	VRA	49.5		45	40	28	
Sunon-Asogli	NG	IPP	200		180	180	138	
Mines reserve	Oil/NG	VRA	80		70	45	20	
Total Thermal			**1005.5**	**46**	**1130**	**765**	**3171**	**31**
Total			**2185.5**		**2230**	**1805**	**10,167**	

Generation capacity of Ghana as at December 2011

Plant	Fuel	Owner	Capacity (MW)				Generation	
			Install	%	Dependable	Reliability	GWh	%
Akosombo hydro	Hydro	VRA	1020		900	0.94	6495	
Kpong hydro	Hydro	VRA	160		140	0.9	1066	
Total hydro			**1180**	**55.5**	**1040**		**7561**	**67.5**
TAPCO	Oil/NG	VRA	330		300	0.7	1137	
TICO	Oil/NG	VRA	220		200	0.8	657	
Tema thermal 1	Oil/NG	VRA	110		100	0.68	559	
Tema thermal 2	NG	VRA	49.6		45	0.85	50	
Sunon-Asogli	NG	IPP	200		180	0.85	1224	
Mines reserve	Oil/NG	VRA	80		70	0.75	12	
Total Thermal			**986.5**	**44.5**	**1130**		**3639**	**32.5**
Total			**2166.5**				**11,200**	

Generation capacity of Ghana as at December 2012

Plant	Fuel	Owner	Capacity (MW)				Generation	
			Install	%	Dependable	Reliability	GWh	%
Akosombo hydro	Hydro	VRA	1020		900	0.94	6950	
Kpong hydro	Hydro	VRA	160		140	0.90	1121	
Total hydro			**1180**	**51.4**			**8071**	**67**
TAPCO	Oil/NG	VRA	330		300	0.7	1061	
TICO	Oil/NG	VRA	220		200	0.8	1168	
Tema thermal 1	Oil/NG	VRA	110		100	0.85	622	
Tema thermal 2	NG	VRA	50		45	0.85	141	
Sunon-Asogli	NG	IPP	200		180	0.68	848	
Mines reserve	Oil/NG	VRA	80		70	0.75	20	
CEL	Oil/NG	IPP	126		70	0.75	94	
Total Thermal			**1116**	**48.6**			**3954**	**33**
Total			**2296**				**12,025**	

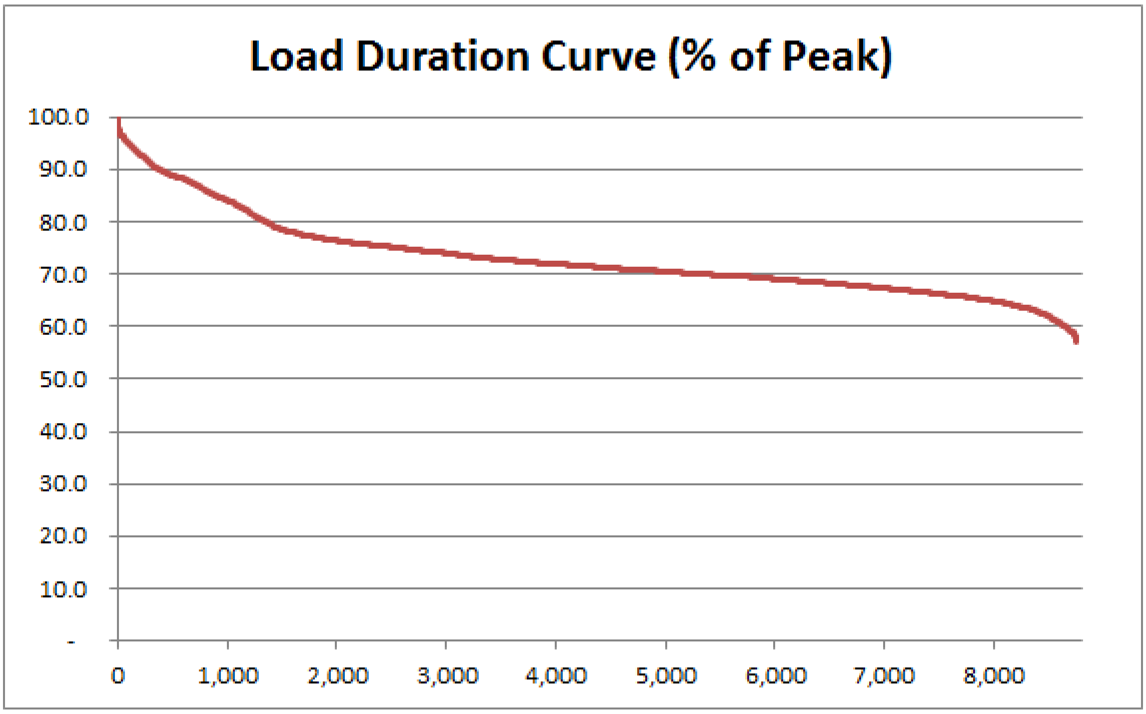
Generation capacity of Ghana as at December 2013

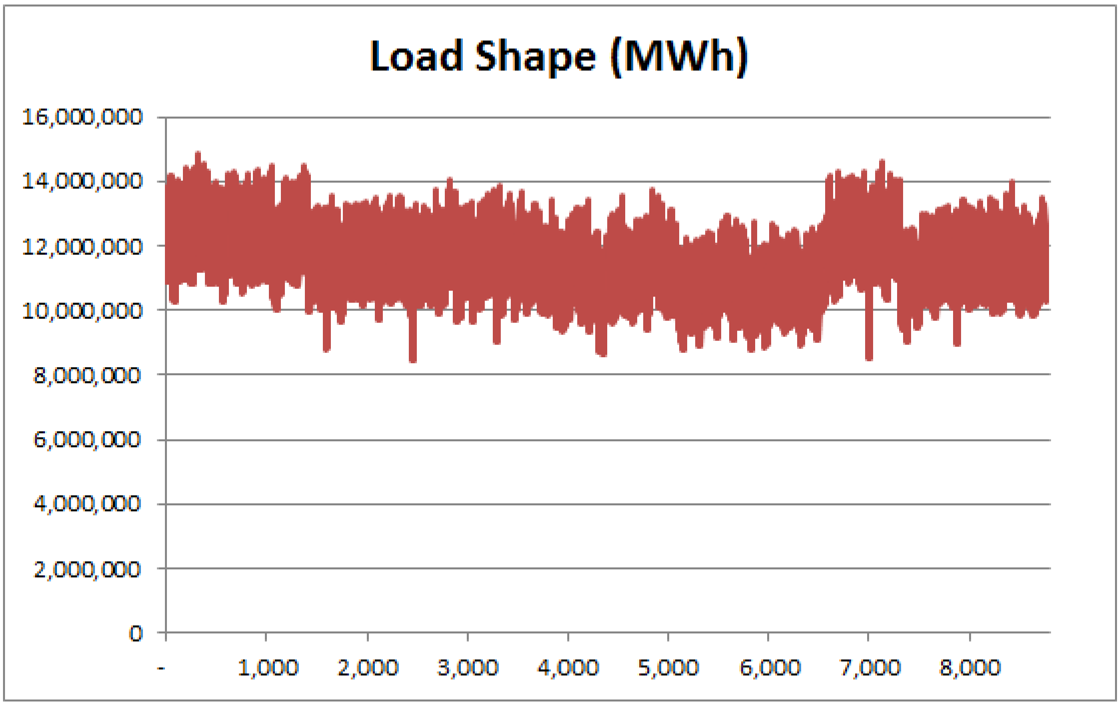
Plant	Fuel	Owner	Capacity (MW)				Generation	
			Install	%	Dependable	Available	GWh	%
Akosombo hydro	Hydro	VRA	1020		900	0.90	6727	
Kpong hydro	Hydro	VRA	160		140	0.90	1144	
Bui hydro	Hydro	BPA	400		380	0.90	362	
Total hydro			**1580**	**55.9**	**1420**		**8233**	**66.3**
TAPCO	Oil/NG	VRA	330		300	0.7	1783	
TICO	Oil/NG	VRA	220		200	0.8	1032	
Takoradi T3	NG	VRA	132		125	0.5	102	
Tema thermal 1	Oil/NG	VRA	110		100	0.85	475	
Tema thermal 2	NG	VRA	50		45	0.85	94	
Sunon-Asogli	NG	IPP	200		180	0.68	694	
Mines reserve	Oil/NG	VRA	80		70	0.75	-	
CEL	Oil/NG	IPP	126		70	0.70	454	
Total Thermal			**1248**		**1090**		**4635**	**33.7**
Navrongo Solar	Solar	VRA	2.5	0.001	2	0.3	3	
Total			**2828**	**44.1**	**2512**		**12870**	

Appendix E Load Curve data for the transformation module

Monthly peak load of Ghana (MW)

Month	Year				
	2010	**2011**	**2012**	**2013**	**2014**
Jan	1435.9	1557.7	1673.8	1751.3	1970.9
Frb	1432.0	1556.3	1636.5	1648.0	1930.9
Mar	1433.6	1606.1	1709.8	1692.3	1802.2
Apr	1456.1	1654.4	1708.3	1791.0	1868.8
May	1470.8	1603.5	1725.5	1853.0	1841.7
Jun	1499.3	1549.5	1671.7	1728.0	1786.0
Jul	1400.0	1538.5	1660.2	1813.8	1823.1
Aug	1396.0	1543.4	1643.9	1832.3	1794.8
Sep	1483.0	1590.9	1526.1	1930.6	1715.6
Oct	1426.2	1623.4	1620.7	1932.3	1940.2
Nov	1479.3	1636.9	1699.9	1942.9	1779.8
Dec	1505.9	1664.6	1728.9	1914.0	1854.9
Average	1451.5	1593.8	1667.1	1819.1	1842.4





Load Shape (MWh)
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
-
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000