UNIVERSITY OF GHANA
COLLEGE OF HUMANITIES

CAPACITY EXPANSION PLANNING FOR ELECTRIC POWER GENERATION IN GHANA

BY

JOSEPH KWAKU BANURO

(10277402)

THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF MASTER OF PHILOSOPHY IN OPERATIONS MANAGEMENT DEGREE

JULY, 2016

DECLARATION

I do hereby declare that this work is the result of my own research and has not been presented by anyone for any academic award in this or any other university. All references used in the work have been fully acknowledged.

I bear sole responsibility for any shortcomings.

……………………………………… ………………………………

Joseph Kwaku Banuro **Date**

(10277402)

CERTIFICATION

I hereby certify that this thesis was supervised in accordance with procedures laid down by University of Ghana.

………………………………… …………………………………

Dr Anthony Afful-Dadzie **Date**

(Supervisor)

………………………………….. ……………………………..

Dr Kwaku Ohene-Asare **Date**

(Co-supervisor)

DEDICATION

I dedicate this work to my uncle, Dr. F.Y. Banuro. Thank you for your love and care, enlightment and inspiration throughout my life. Thank you for always believing in me and supporting me at all times.

ACKNOWLEDGEMENT

The compilation of this thesis could not have been successfully done without the support of some dedicated people. I therefore wish to thank some individuals who have contributed in diverse ways to making this work a success.

First, I am grateful to the almighty God for granting me the strength to complete this work successfully.

I would like to particularly express my greatest appreciation to Dr. Anthony Afful-Dadzie for his immerse support and encouragement during the planning and development of this research. His willingness to give his time so generously and the designing of the model codes have all been very much appreciated. Undoubtedly, without his help, this study would have been time consuming and very difficult to accomplish. I am also thankful to Dr Kwaku Ohene-Asare for his encouragement.

Many thanks go to some workers of the Volta River Authority (VRA) and the Ghana Grid Company (GRIDCo) who assisted me in data collection. Without their help, the work would have been next to impossible.

Special thanks go to my parents Mr. Daniel Banuro and Mrs. Kasing Banuro, my siblings Sullobie Banuro, Sullo Banuro, N-yemmor Banuro, Linda Banuro, Issac Banuro and John Banuro and the entire Banuro family for your support and encouragement throughout my academic pursuits.

Finally, I am grateful to my friend Caleb Boadi for his input in making this work a success.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AIMMS	Advance Integrated Multidimensional Modelling Software
AMPL	A Mathematical Programming Language
BPA	Bui Power Authority
CCGT	Combined Cycle Gas Turbine
DFO	Distillate Fuel Oil
ECG	Electricity Company of Ghana
ECOWAS	Economic Community of West African States
EC	Energy Commission
GAMS	General Algebraic Modelling System
GEP	Generation Expansion Planning
GGMP	Ghana Generation Master Plan
GRIDCo	Ghana Grid Company
GSGDA	Ghana Shared Growth and Development Agenda
GW	Gigawatt
GWh	Gigawatt hour
GDP	Gross Domestic Product
HFO	Heavy Fuel Oil
IFC	International Finance Corporation
IPPs	Independent Power Producers
IEA	International Energy Agency
ISSER	Institute of Statistical and Social Economic Research
KTPP	Kpong Thermal Power Plant

KWh	Kilowatt hour
LCO	Light Crude Oil
MCC	Millennium Challenge Corporation
MDGs	Millennium Development Goals
MIGA	Multilateral Investment Guarantee Agency
MILP	Mixed Integer Linear Programming
MoEn	Ministry of Energy
MRP	Mines Reserve Plant
MW	Megawatt
MWh	Megawatt hour
NDPC	National Development Planning Corporation
NED	Northern Electricity Department
NG	Natural Gas
OCGT	Open Cycle Gas Turbine
O&M	Operating and Maintenance Cost
PSEC	Power System Energy Consulting
PURC	Public Utilities Regulatory Commission
TAPCO	Takoradi Power Company
TICO	Takoradi International Company
TT1PP	Tema Thermal Power Plant 1
TT2PP	Tema Thermal Power Plant 2
WAPP	West Africa Power Pool
VALCO	Volta Aluminum Company

VRA	Volta River Authority

LIST OF PUBLICATIONS

Banuro, F.Y., Ntiri-Ampomah, A., & Banuro, J.K. (2017). Contradictions in TQM implementation: A proposed balance from the Ghanaian perspective. *The TQM Journal*, *29*(4). *Accepted and forthcoming.*

Afful-Dadzie, A., Afful-Dadzie, E., Iddrisu, A., & Banuro, J.K. (2017). Power Generation Capacity Planning Under Budget Constraint in Developing Countries. *Applied Energy*, *188*, 71-82.

Banuro, F.Y., & Banuro, J.K. (2014). Balanced Sourcing as an Important Attribute of Operations Strategy: Reality or Myth Among Ghanaian Firms? *African Journal of Management Research*, *21*(2), 1-7.

ABSTRACT

The Ghanaian electric power system, like most Sub-Saharan African countries, is bedevilled with the problem of inadequate generation of electric power amidst growing demand for electricity. Governments over the years have tried to tackle the issue of inadequate generation capacity and supply of electricity in Ghana to meet the increasing demand for electric power. Yet electricity supply in Ghana remains erratic and inconsistent. The purpose of this study was to develop a long-term (20-years) electricity generation expansion plan for Ghana's electricity sub-sector that takes into account important attributes specially related to Ghana, such as budget constraint. The study employs multi-period stochastic mixed-integer linear programming (MILP) to model and solve the problem of determining the *technology type, timing* and *number of units* of generators to add to the existing capacity under uncertain demand taking into account budget constraint. Secondary data was used to estimate all the model parameters. Periodic electricity demand scenarios were obtained by assuming that the uncertain demand follows a triangular distribution with a minimum increase of 1%, the most likely increase of 7% and a maximum increase of 15% over the immediate past year's electricity demand. The proposed multi-period stochastic MILP model was run for two cases: without budget constraint which depicts the case where there are sufficient funds to undertake an expansion plan and the budget constraint case, where the expansion plan is faced with lack of funds. The imposition of budget constraint is a departure from the typical generation capacity expansion models found in the literature and helps explain generation expansion pattern in Ghana. The expected values of the objective function and the generation expansion plans considering no budget constraint and budget constraints were optimized in order to draw analogy. It is observed that the presence of budget constraint sometimes forces the decision maker to take decisions that might be sub-optimal compared to when sufficient funds are available.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Electricity has become a basic necessity of life. Its form and modes of use are expanding every day because it is the easiest and least expensive transportable form of energy (Sharma, 2009). It is particularly crucial for emerging economies whose national developmental agenda oblige steady availability of electric power. Interestingly, an estimated 1.2 billion people; roughly, one sixth of the world's population lack access to electricity supply, of which almost 80% of them are in developing countries especially in Sub-Saharan Africa and South Asia (World Bank, IFC, & MIGA, 2013).

Demand for electric power in Sub-Saharan Africa has increased dramatically in recent times due to modernisation. Key sectors of the economy such as manufacturing, health, construction, entertainment, education and communication significantly depend on the generation and supply of electric power for their activities. However, Sub-Saharan Africa, like most developing regions, is in the midst of electric power crisis due to inadequate generation capacity and unreliable supply. The total installed generation capacity of Sub-Saharan Africa is lower compared to any other region in the world (International Energy Agency (IEA), 2014). The total installed generation capacity of all the countries in Sub-Saharan Africa was around 90 gigawatt (GW) in 2012, less than the installed capacity of Spain (Deloitte Conseil, 2015; IEA, 2014). Excluding South Africa, the installed generation capacity of the remaining Sub-Saharan Africa countries reduces to a mere half of the total (IEA, 2014). Sub-Saharan Africa's installed generation capacity has remained largely stagnant, with growth rates of about half of those found in other developing regions (Eberhard, Rosnes, Shkaratan, & Vennemo, 2011). Consequently, there is a wide gap in electricity generation capacity between Sub-Saharan Africa and the other developing regions. In general, generation capacity should be at the same growth rate as the economy in order to keep pace with electricity demand increase (Eberhard, Foster, Briceño-Garmendia, Ouedraogo, Camos, & Shkaratan, 2008). However, this is not the case in Sub-Saharan Africa.

The insufficient electricity generation capacity ultimately leads to low rates of electricity access. About a quarter of the population of Sub-Saharan Africa has access to electricity, as opposed to a double of that in South Asia (World Bank, IFC & MIGA, 2013). With the current trends, very few Sub-Saharan African countries will reach universal access to electricity by the projected year of 2050. Due to the region's insufficient electricity generation capacity and electricity access, it is obvious that per capita consumption of electricity is lower, averaging just 400 kilowatt hour (KWh) annually, with the average falling to less than 200 KWh without South Africa (IEA, 2014). By comparison, the annual average per capita consumption in the other developing regions is 1,500 KWh (IEA, 2014).

Inadequate generation capacity and lack of access to electricity in the region is a main cause of low levels of productivity which is a serious drag on long-term competitiveness (Eberhard et al., 2008). For instance, manufacturing firms in Sub-Saharan Africa experience electric power outages on an average of 56 days per year, which is only one day in ten years in United States of America (World Bank, 2013). As a result, the industrial sector in Sub-Saharan Africa experiences an increase in their production costs due to a switch to back-up generators. Insufficient electricity reduces economic activities such as opening of new factories, businesses and institutions that have the potential to increase employment, improve living standards of citizenry and help in achieving the Millennium Development Goals (MDGs).

The electric power problems in Sub-Saharan Africa countries can be seen in the growing recourse to kneejerk actions such as the advent of emergency electric power barges (Eberhard et al., 2011). To increase generation capacity in order to deal with electricity supply outages, countries enter into temporary leases for generation capacity. These temporary contracts are usually costly (Eberhard et al., 2011). For instance, emergency electric power barges that started operating in Ghana in 2015, have their costs approaching 3 percent of gross domestic product (GDP). Clearly, the prevalence of emergency electric power barges represents lack of a comprehensive long-term planning framework tailored to the region's environment (Eberhard et al., 2011).

The electric power problems in Sub-Saharan Africa are deeply rooted in the region and the required investment to overcome the challenge of generation capacity is daunting. In Ghana, for example, an estimated $4.7 billion of investments is required to catch up and/or upgrade Ghana's current electric power system (Millennium Challenge Corporation (MCC), 2012). The annual investment for additional generation capacity alone is estimated to be between $200 and $280 million to cater for increasing electricity demand and keep pace with anticipated economic growth (MCC, 2012). Besides the huge financial investment required, a major concern, perhaps even more important for Sub-Saharan Africa electric power systems is developing a planning framework tailored to the region's environment to guide capacity expansion. Planning for electric power system expansion is essentially a projection of how the system should grow, usually in the long-term while taking into account uncertainties (Al-shaalan, 2011). In the electric power system, planning must be done in the face of many uncertainties which make the planning process indispensable to provide the necessary information to enable decision to be made today about many years to come (Al-shaalan, 2011). Examples of these uncertainties are: future electricity demand, price and availability of fossil fuels (coal, diesel, natural gas etc.), weather variation and economic growth which characterize most developing countries, as well as technical, economic and environmental constraints (Jin, 2012; Sharma, 2009; Shiinat & Birge, 2003).

In Ghana, electricity has become one of the most important inputs for economic development (Adom, 2011). According to the Ghana Shared Growth and Development Agenda (GSGDA), the electricity sub-sector will seek to ensure a secured and reliable supply of high quality electric power to all sectors of the economy as Ghana positions itself as a regional exporter of electricity and a net exporter of oil (NDPC, 2010). Ghana discovered oil and gas in commercial quantities in 2007, which implies the Ghanaian economy is at the verge of attracting local and foreign companies into the oil industry whose operations rely heavily on electricity. However, Ghana, like many Sub-Saharan African countries, is bedevilled with lack of sufficient electric power, which has culminated in the loss of a significant amount of productivity in the country (ISSER, 2014). The loss in productivity is an accumulation of time lost in production because of lack of additional generation capacity to bridge the supply and demand gap. Governments over the years have tried to tackle the issue of inadequate generation capacity and supply of electricity in Ghana to meet the increasing demand for electric power. Yet electricity supply in Ghana remains erratic and inconsistent. The problem with Ghana’s electric power system like most Sub-Saharan Africa is lack of a comprehensive long-term planning framework tailored to the Ghanaian environment to guide capacity expansion.

It is in light of this precarious situation that this current study attempts to develop a long-term planning framework for generation capacity expansion in the case of Ghana. Planning for capacity expansion is a key area of research in Operations Research/Management Science. In this thesis the generation expansion planning (GEP) problem is solved using stochastic optimization technique which is one of the techniques for handling uncertainties inherent in electric power system planning (Shiina, 2011). It is envisaged that this approach will guide decision making in the area of generation capacity expansion in order to bridge the electricity deficit in Ghana and by extension in Sub-Saharan Africa.

1.2 Statement of the Problem

Electric power is a key infrastructural element for economic development. It is a commodity that underpins a wide range of goods and services that improve the quality of life and increase productivity. In fact, without sufficient electric power supply, homes, businesses and the society at large cannot function to full capacity. Adequate generation of electric power and electricity access is therefore, a necessary condition for achieving a sustained economic growth.

Despite the huge benefits that come with the use of electric power, the Ghanaian electric power system like most Sub-Saharan Africa is plagued with inadequate generation of electric power amidst growing demand for electricity (Adom, Bekoe, & Akoena, 2012). In Ghana, power usually goes off indiscriminately and in most of the times without prior notification to consumers making it difficult for the various consumer categories (residential, commercial and industrial) to reorganise their activities accordingly. Many factors are responsible for such unreliable supply of electric power. These include the high demand for electricity which exceed supply, weather variation that affects hydroelectric power generation - a major source of electric power generation in Ghana, inadequate reserve margin among others (Tractebel Engineering, 2011). These, coupled with a lack of a comprehensive long-term plan tailored to the Ghanaian environment to guide new generation capacity expansion, have contributed to erratic power supply in Ghana.

Ghana’s current national long-term generation capacity expansion plan (Tractebel Engineering, 2011) is based on the premise of the availability of sufficient funds for financing the needed generation capacity to meet future demand. This study seeks to argue that planning from this point of view particularly in the Ghanaian context is a recipe for disaster. For it is almost certain sufficient funds will never be available. When this is the case, this long-term plan become irrelevant and never implemented. This further leads to kneejerk decisions that are too costly to a developing country. Assuming sufficient funds availability also contribute to the lack of reliable information on anticipated level of unserved energy. It is therefore important that capacity expansion plans, in a developing country such as Ghana, are looked at from the point of view of budget constraint to better enable the country to plan accordingly. Budget constraint could be envisioned as equivalent to the case of setting aside a percentage of the national GDP solely for the financing of additional capacities for electricity generation.

This study attempts to develop a long-term plan for generation expansion in Ghana based on stochastic optimization to determine the *technology type*, *timing* and *number of units* of generators to build taking into account the constraint on availability of funds and uncertainty in electricity demand.

1.3 Objectives of the Study

The main aim of this study is to develop a long-term (20-years from 2016 to 2035) electricity generation expansion plan for Ghana's electricity generation system. Specific objectives to be achieved are:

1 To employ stochastic optimization technique in determining the optimal *technology type*, *timing* and *number of units* of power generators to add to the existing generation system of Ghana taking into account budget constraint.

2. To quantify the level of unserved electricity demand under budget constraint in order to help decision makers appreciate the consequences of capacity expansion decisions and the attendant effect on the economy.

3. To establish the optimal level of savings to meet projected electricity demand within the planning horizon.

1.4 Research Questions

This thesis seeks to answer the following research questions:

1. What *technology type*, *timing* and *number of units* of power generators are to be added to the existing generation system of Ghana taking into account budget constraint?

2. What are the anticipated levels of unserved electricity demand and the attendant consequences to Ghana's economy due to lack of funds for financing new generation capacity?

3. What levels of periodic savings are needed in order to significantly reduce the levels of unserved electricity demand over the planning period?

1.5 Significance of the Study

The current study (Tractebel Engineering, 2011) on long-term capacity expansion plan for Ghana has assumed the availability of sufficient capital investment funds. However, for a developing country like Ghana, it is always the case that sufficient funds will never be available and thereby leaving this long-term plan inapplicable. In the face of the inapplicability of this plan, actions are taken that border on quick fix solution that may be sub-optimal and costly to the country. This study therefore seeks to develop a comprehensive long-term capacity expansion model for GEP that takes into account constraint on the availability of funds for financing the needed capacity. The study asks the question of what is best to do in the face of financial constraint. Approaching the GEP problem from this angle will help to better plan for the anticipated level of unserved electricity demand as a result of the inability to provide enough new generation capacities due to financial constraint. It is not difficult to see that financial constraint can lead to actions (optimal of course under such situation) that may be deemed sub-optimal when judged from the point of view of sufficient funds availability.

It is also significant that though GEP with multi-period stochastic MILP model is not new (Rebennack, 2014; Shiinat & Birge, 2003), the current study is the first of its kind to apply the technique to develop a long-term generation expansion plan for Ghana. Even more noteworthy is the fact that no evidence has been discovered by this study of anyone ever using multi-period stochastic MILP model for GEP that considered periodic budget constraint in the context of a developing country. Hopefully, the findings of this research should become a cardinal reference document in this direction for future researchers and policy makers, academic or otherwise. Also, the approach for the current work could become a template for solving the GEP problem in Ghana and beyond.

In a nutshell, this study intends to help electric power generation entities (public and private) to determine the *technology type, timing* and *number of units* of new generators to build in order to meet future electricity demand in a least cost manner, taking into account the financial constraint faced by Ghana.

1.6 Methodology and Data Analysis

Traditionally, GEP has been based in a regulated environment and the objective was minimization of the total system wide plan cost while meeting electricity demand growth. This planning exercise is still considered valid in countries including Ghana that are still technically operating under the regulated system. In this study, therefore, GEP was modelled under a regulated environment.

In addition, a multi-period stochastic MILP model was developed. The model was run for two cases: with no budget constraint and with budget constraint. Secondary data was used to estimate all the model parameters. These data were obtained from the Ghana Generation Master Plan (GGMP) (Tractebel Engineering, 2011). Electricity demand, a major uncertain parameter, was considered. The expected changes in demand for future years were modelled and 20 scenarios generated for each year. A triangular distribution of the demand is assumed. The expected values of the objective function and the generation expansion plans considering no budget constraint and budget constraints were optimized in order to draw analogy. The optimization model was written in General Algebraic Modelling System (GAMS) software and solved using an ILOG CPLEX 12.6.0.0 solver.

1.7 Thesis Outline

This study is organized in six chapters. Chapter 1 gives the background to the study, the problem statement, the research objectives, the research questions and the significance of the study. Chapter 2 gives an overview of the electric power system in Ghana. Chapter 3 reviews the literature on the study area. In this chapter, capacity expansion planning and optimization theory, specifically stochastic programming model, are reviewed. Chapter 4 focuses on the development of the proposed stochastic optimization model for this study. It begins with the model assumptions and notations, presents the proposed stochastic MILP model and discusses the model parameters and software employed. Chapter 5 presents data and discusses the results for capacity expansion for electric power generation in the case of Ghana. Finally, Chapter 6 concludes the study and offers recommendations for policy, based on the findings of this study as well as recommendations for future research.

CHAPTER TWO

OVERVIEW OF THE ELECTRIC POWER SYSTEM IN GHANA

2.1 Introduction

This chapter presents a general overview of the electric power system in Ghana with particular attention to electric power generation system. The chapter first gives the history of electricity generation in Ghana followed by the current electricity system-facts and figures. The chapter ends with a look at electricity market structure in Ghana.

2.2 History of Electricity Generation in Ghana

The history of electricity generation in Ghana can be traced to the colonial times in 1914 when electricity supply, sponsored by the government, was initiated in Sekondi in the Western Region of Ghana (ISSER, 2005). From that time, the electricity sub-sector has undergone various transitional reforms and restructuring in a bid to ensure uninterrupted electricity supply to Ghanaians. The historical path of electricity generation in Ghana can be put into three main phases (ISSER, 2005):

- "*Before the Hydro Years*", refers to the period before the construction of the Akosombo hydroelectric power plant in 1966
- "*The Hydro Years*", covers the period from 1966 to the mid-eighties
- "*Thermal Complementation Years*", from the mid-eighties to date when thermal plants are used to supplement hydroelectric power generation.

2.2.1 Before the Hydroelectric Power Generation

Prior to the construction of Akosombo hydroelectric power plant, electricity generation and supply in Ghana was carried out with a number of isolated diesel generators across the country. The owners of these generators were industrial establishments such as mines, factories, municipalities and other institutions (ISSER, 2005).

The first government sponsored public electricity supply in Ghana was established in Sekondi in 1914 to support the operations of the then Gold Coast Railway Administration. In fact, the Railway Administration was the operator of the system at the time (ISSER, 2005). By 1928, the supply from the system was extended to neighbouring Takoradi to support the railway operations in that city. In a bid to emulate the Railway Administration, the Public Works Department also initiated public electricity supply systems and commenced limited direct current to Accra in 1922 followed by a large alternating current project which commenced in 1924. Subsequently, electricity was extended to Koforidua, Kumasi, Winneba, Cape Coast, Swedru, Tamale, Bolgatanga and to other municipalities in the country.

In 1947, the operation of public electricity supplies by Railways Administration and Public Works Department was handed over to the Electricity Department within the Ministry of Works and Housing. Amongst the major electricity generation projects undertaken by the Electricity Department was the construction of the Tema Diesel Power Plant. The plant was built in 1956 with an initial capacity of 1.95 MW. Between 1961 and 1964, it was expanded to 35 MW with the addition of ten 3 MW diesel generators and other units of smaller sizes. It was believed that the plant when completed would be the single largest diesel power station in Africa (ISSER, 2005). The diesel power station served the Tema municipality and some parts of Accra.

The total electricity supplied and demanded from 1914 to 1966 could not be accurately determined due to the dispersed nature of the generation resources and the unreliable nature of electricity supply. In addition, most of the towns served had supply for only part of the day due to inadequate supply. There was therefore very little growth in electricity consumption. Total recorded electric power demand of about 70 MW with the first switch on of the hydro power station can be used as a proxy for level of electricity demand in Ghana at the time (ISSER, 2005).

2.2.2 Hydroelectric Power Generation

The need for hydroelectric power can be linked with efforts to develop the huge bauxite reserves of Ghana as part of integrated bauxite to aluminium industry. The first and the biggest hydro plant to be built is the Akosombo hydro plant with an installed capacity of 1,020 MW located in Akosombo in 1966. A year after the Akosombo hydroelectric station was commissioned; most of the major electricity consumers were weaned off diesel-powered plants and served from Akosombo. The electricity generated from the Akosombo plant serves as a force behind Ghana’s economic development and also supported neighbouring countries such as Togo and Benin by exporting power to these countries (ISSER, 2005).

Ghana’s expanding industry and economic development caused greater demand for electric power, so in 1982, a second hydroelectric power plant called the Kpong hydro plant with an installed capacity of 160 MW was developed just downstream of Akosombo. The Kpong plant was to supplement that of Akosombo plant. Other hydroelectric power sources were discovered, notably the Bui hydroelectric plant which was to be developed at a later date. But the susceptibility of Ghana’s electric power system to the whim of the weather was exposed. There were three years of severe drought that affected the inflow of water into the reservoirs for the two hydroelectric power plants. Consequently, electricity generation from the hydroelectric power plants declined causing power rationing during those three years. So the search for other sources of generating electricity was initiated.

2.2.3 Thermal Complementation

In 1983, Volta River Authority (VRA), the operator of Akosombo and Kpong hydroelectric power plants, undertook an expansion study called the Ghana Generation Planning Study (ISSER, 2005). The planning study which was completed in 1985 confirmed the need for thermal plants to provide a reliable complementation to the hydro generating sources at Akosombo and Kpong. Subsequently, a study was carried out to determine the best type of technology for the thermal plants to be developed. The study, called the Combustion Turbine Feasibility Study, was completed in 1990. The study recommended the addition of combustion turbine namely; combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT) as the technology choices for thermal plants in Ghana (ISSER, 2005). CCGT works on closed cycle (steam from waste heat is run through a steam turbine to provide supplemental electricity). It has a better thermal efficiency but complex with high capital cost but a low running cost. On the other hand, OCGT works on open cycle (waste heat is exhausted to atmosphere). OCGT has a low thermal efficiency but simple with less capital cost but a high running cost. OCGT plants are sometimes installed as peaking capacity (capacity to be used at peak periods).

With continuous increase in the demand for electricity, another study, Takoradi Thermal Plant Feasibility Study was completed with a recommendation for the construction of a 600 MW plant, with an initial 330 MW CCGT commissioned in 1998 (ISSER, 2005). A year later and in line with Government’s policy to allow for private participation in electricity generation in

Ghana, the VRA entered into a joint venture arrangement with CMS Energy of USA to expand the Takoradi Thermal Plant to 550 MW with the addition of 2x110 MW OCGT plants. The two OCGT units became operational in the year 2000. With the expansion of the Takoradi Thermal Plant, thermal generation increasingly started playing a major role within the electricity generation mix in Ghana.

2.3 Electricity System in Ghana- Facts and Figures

2.3.1 Existing Generation System

Currently, electricity in Ghana is generated through two main sources namely; hydro and thermal. According to data gathered from VRA and Energy Commission (EC) of Ghana, the existing generating system in the country has 3,859.6 MW of installed capacity and a dependable capacity of 3,416.9 MW as at the end of year 2015 (Energy Commission, 2015b; VRA, 2015). These figures include capacity owned by private sector developers and two additional thermal plants completed and awaiting to be commissioned. Note that installed capacity also known as nameplate capacity is the maximum capacity a power plant is designed to run at while dependable capacity is the load-carry ability of a power plant over a specified period of time.

In terms of hydro thermal share, there are three hydro plants that account for 1,580 MW of the generation capacity or 40.94% of the national total. The combined dependable capacity for the hydro plants stood at 1,385 MW as at the end of year 2015. The share of installed generation capacity for thermal plants is 2,277.1 MW, representing 59% of the total and the dependable capacity is 2,030 MW. Note that thermal plants are either CCGT or OCGT technologies (see Table 2.1). The remaining generating capacity is solar with installed capacity of 2.5 MW representing 0.06%. It follows that, at present, thermal capacity share is much higher than hydro due to the addition of more thermal plants over the years. This means the generation system is gradually being dominated by thermal and Ghanaians should be ready to pay much higher tariff for electric power. Details of the existing generating system are given in Table 2.1.

Table 2.1: Existing generation system in Ghana (End of December, 2015)

Name of Plant	**Type**	**Fuel Type**	**Commissioning Year**	**Plant Location**	**Installed Capacity (MW)**	**Dependable Capacity (MW)**
Akosombo	Hydro	Water	1966	Akosombo	1020	900
Kpong	Hydro	Water	1982	Kpong	160	140
Bui Power Authority	Hydro	Water	2013	Bui	400	345
Aboadze T1 (TAPCO)	CCGT	LCO/NG	1998	Takoradi	330	300
Aboadze T2 (TICO)	OCGT	LCO/NG	2000	Takoradi	330	300
Mines Reserve Plant (MRP)	OCGT	DFO/NG	2007	Tema	80	40
Tema Thermal Plant 1 (TT1PP)	OCGT	LCO/NG	2009	Tema	126	110
Tema Thermal Plant 2 (TT2PP)	OCGT	DFO/NG	2010	Tema	49.5	45
Takoradi T3	CCGT	LCO/NG	2012	Takoradi	132	120
Kpong Power Plant (KTPP)	OCGT	LCO/NG	Awaiting	Kpong	220	200
Sunon Asogli*****	CCGT	NG	2010	Tema	198	180
Sunon Asogli Expansion Phase I*****	CCGT	NG	Awaiting	Tema	180	160
Trojan Power Ltd*****	OCGT	DFO	2010	Tema	25.6	20
Cenit Energy Ltd*****	OCGT	LCO	2012	Tema	126	110
Genser Power Ghana Ltd*****	OCGT	DFO	2012	Tema	5	5
Ameri Energy*****	CCGT	NG	2015	Takoradi	250	220
Karpowership******	CCGT	HFO/NG	2015	Tema	225	220
VRA Solar	Renewable	Sunshine	2013	Naverongo	2.5	1.9
		Total			**3859.6**	**3416.9**

Source: Energy Commission (2015b) and VRA (2015)

*Owned by IPPs
******Emergency power plant

The existing generating system in Ghana is mainly owned by two public institutions namely VRA and Bui Power Authority (BPA) with a considerable share owned by the private sector. Until the year 1999, the total electricity system was owned by the VRA. Since the year 1999, private sector has also participated in power generation on their own or in partnership with the VRA. The majority of installed capacity is owned by VRA and BPA representing 80% of the total installed capacity, which includes 1580 MW of hydro, 1517.5 MW of thermal and 2.5 MW of solar generation capacity. Thus, VRA and BPA account for 3,100 MW of the total generation capacity. Balance installed capacity of 759.6 MW (3,859.6 MW – 3,100 MW), which is totally thermal plants, is owned by IPPs.

2.3.2 Electricity Generation

In early stages, the electricity demand of the country was mainly supplied by hydro generation and the contribution from thermal generation was minimal. With time, thermal generation has become prominent. Electricity Generation during the last fifteen years is summarized in Table 2.2 and graphically shown in Figure 2.1. The generation figures for hydro and thermal as well as import are presented in Table 2.2.

Table 2.2: Electricity generation, 2000 to 2014

	Hydro Generation		**Thermal Generation**		**Import**		**Total**
Year	**GWh**	**%**	**GWh**	**%**	**GWh**	**%**	**GWh**
2000	6609	81.72	614	7.59	864	10.68	8087
2001	6609	79.43	1250	15.02	462	5.55	8321
2002	5036	59.82	2237	26.57	1146	13.61	8419
2003	3886	56.96	1996	29.26	940	13.78	6822
2004	5281	76.35	758	10.96	878	12.69	6917
2005	5629	74.04	1159	15.24	815	10.72	7603
2006	5619	62.03	2811	31.03	629	6.94	9059
2007	3727	50.28	3251	43.86	435	5.87	7413
2008	6195	72.04	2129	24.76	275	3.20	8599
2009	6877	75.11	2081	22.73	198	2.16	9156
2010	6996	68.10	3171	30.87	106	1.03	10273
2011	7561	67.02	3639	32.26	81	0.72	11281
2012	8071	66.42	3953	32.53	128	1.05	12152
2013	8233	63.85	4635	35.94	27	0.21	12895
2014	8387	64.47	4572	35.14	51	0.39	13010
Last 5 year average growth rate (%)	4.09		18.33		-0.41		7.35
Last 10 year average growth rate (%)	7.04		26.60		-12.77		7.01

Last 15 year average growth rate (%)	4.26	26.84	-3.62	4.04

Source: Energy Commission (2014), Energy Commission (2015c) and Tractebel Engineering (2011)

It is observed from Table 2.2 that total electricity generation has increased from 8,087 GWh in the year 2000 to 13,101 GWh in the year 2014. This represents an increase of 62.26% over the period and an average annual growth of 4.04%. However, during the last 5 years, generation has been growing at a rate of 7.35% per annum due to the addition of new capacity over the years. Generally, an increasing trend is seen in electricity generation although occasionally, some particular years have recorded a decline from the previous year's generation as seen with the years 2003 and 2007. The decline observed in the year 2007 for hydro for example, is attributed to the decline in the water level of the Akosombo Dam which led to a shortfall in hydro generation.

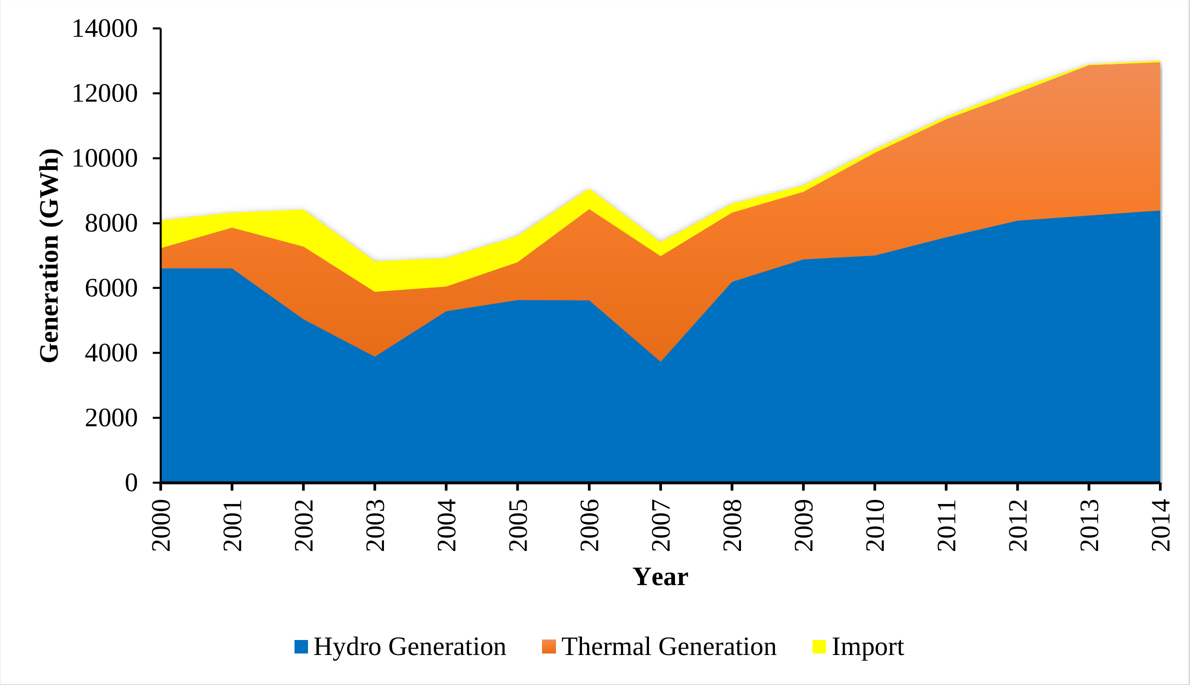

Figure 2.1: Hydro thermal share in electricity generation in recent past (**Source:** Author's computation with information from Energy Commission (2014) and Energy Commission (2015c))

In terms of the hydro and thermal generation share (see Figure 2.1), hydro sources contribution is higher, an average of 67.84% of total electricity generation in the last fifteen years while thermal sources and imports contribution to electricity generation are at an average of 26.25% and 5.91% respectively. However, thermal sources contribution has increased in the latter years, largely due to the addition of new thermal plants to mainstream generation in the last five years or so. It remains, however, that for the past fifteen years, Ghana's electricity generation is mainly hydro dominated.

2.3.3 Past Electricity Demand

Electricity demand during the last fifteen years is summarized in Table 2.3 and graphically shown in Figure 2.2. The demand is presented from domestic demand, export as well as transmission losses. Note that the domestic consumption includes the generation facilities consumption and load centres usage.

Table 2.3: Electricity demand in Ghana, 2000 to 2014

Year	Domestic GWh	Export GWh	Losses GWh	Domestic +Export+Losses GWh	Generation GWh	Peak Demand MW
2000	7446	392	229	8067	8087	1161
2001	7733	302	264	8299	8321	1181
2002	7423	612	368	8403	8419	1227
2003	5847	604	316	6767	6822	1135
2004	6022	665	205	6892	6917	1049
2005	6682	639	249	7570	7603	1325
2006	7945	754	318	9017	9059	1393
2007	6608	246	228	7082	7413	1274
2008	7587	538	303	8428	8599	1367
2009	8030	752	342	9124	9156	1423
2010	8835	1036	380	10251	10273	1506
2011	9994	691	538	11224	11281	1665
2012	10893	667	522	12082	12152	1729
2013	11688	530	571	12788	12895	1943

2014	11870	522	565	12958	13010	2061
Last 5 year average growth rate (%)	8	-4	12	7	7	8
Last 10 year average growth rate (%)	7	8	12	7	7	7
Last 15 year average growth rate (%)	4	12	9	4	4	5

Sourec: Energy Commission (2014), Energy Commission (2015c) and Tractebel Engineering (2011)

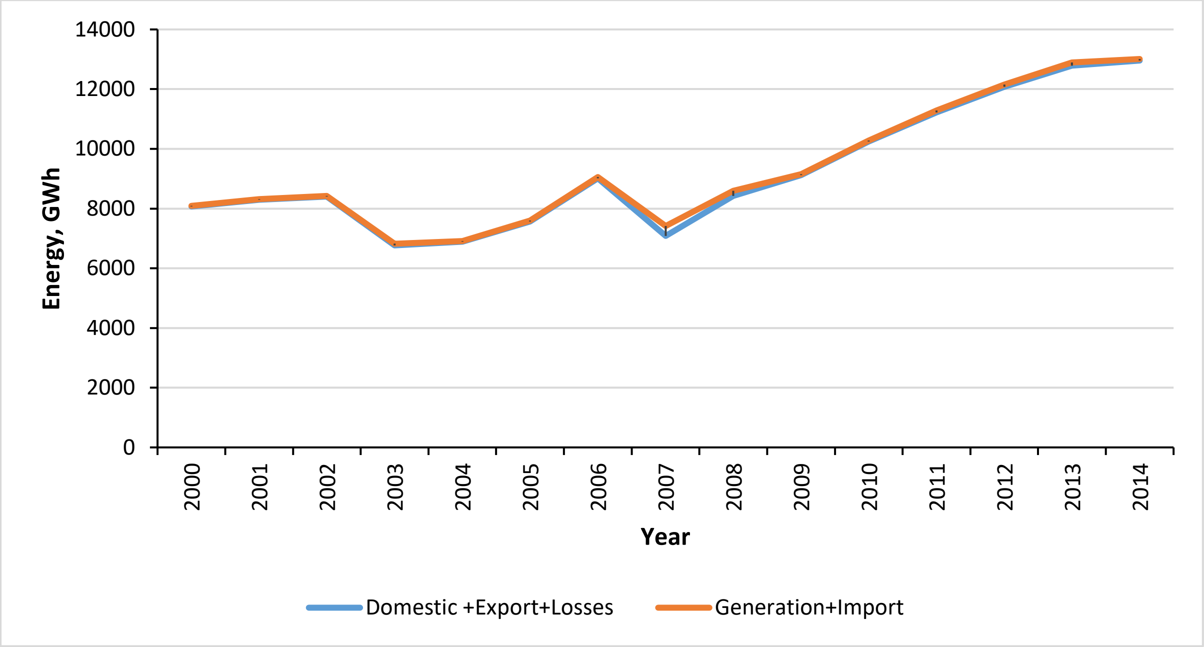

Figure 2.2: Electricity demand in Ghana, 2000 to 2014 (**Source:** Author's computation with information from Energy Commission (2014) and Energy Commission (2015c))

Demand for electricity in Ghana during the last 15 years has been growing at an average rate of about 4 % per annum while peak demand has been growing at a rate of 5% per annum as shown in Table 2.3. However, the peak demand has grown at a rate of 8% during the last 5 years and energy demand has been growing at a rate of 7% per annum. In 2014, 12,958 GWh of electricity was generated to meet the demand which had been only 8,067 GWh fifteen years ago. The recorded peak demand within the year 2014 was 2,061 MW which was 1,943 MW in year 2013 and 1,161 MW fifteen years ago. Generally, domestic demand for electricity has seen an increasing trend due to economic growth, urbanization and the ongoing national electrification scheme. As observed in Figure 2.2, electricity demand is closing up the gap in terms of total electricity generation indicating that generation capacity is gradually running out.

Note that the demand does not include suppressed demand (unmet demand) which is estimated to be about 3% of load (Tractebel Engineering, 2011). The suppressed demand has been found to be from two causes: inadequate generation capacity and lack of electricity access (Tractebel Engineering, 2011). Currently, VALCO, the government-owned smelter, is suffering from supply shortages representing the major part of suppressed load of Ghana. At peak load, some partial domestic load shedding is sometimes necessary depending on the availability of generation units that also constitute suppressed demand.

2.3.4 Electricity Imports and Exports

In the year 2003, Ghana signed the ECOWAS Energy Protocol which calls for the elimination of cross border trade barriers to energy trade and encourages investment in the energy sector. This agreement, along with the West African Power Pool (WAPP) agreement, is expected to lead to a more active regional import and export electricity market. These agreements have potentially important benefits for Ghana. Demand for electricity is growing rapidly throughout the region, which simultaneously creates a larger market for Ghana to trade electricity in the larger ECOWAS region. Currently, Ghana’s electricity trading partners are Togo, La Cote D’Ivoire, Burkina Faso and Benin, with whom electricity is either imported or exported. For instance, Ghana has an exchange agreement with La Cote D’Ivoire for up to 200 to 250 MW of electricity import/export as need arises on either side (PSEC & GRIDCo, 2010).

The difference between imports and exports of electricity is the net imports. If this difference is positive, it implies that imports for a particular year are greater than exports of electricity for that year. If this happens to be the case, there will be a reduction in the country’s foreign reserves. On the other hand, negative net imports will improve the country's foreign reserves. Figure 2.3 shows the levels of imports and exports of electricity and the net imports from the period 2000 to 2014.

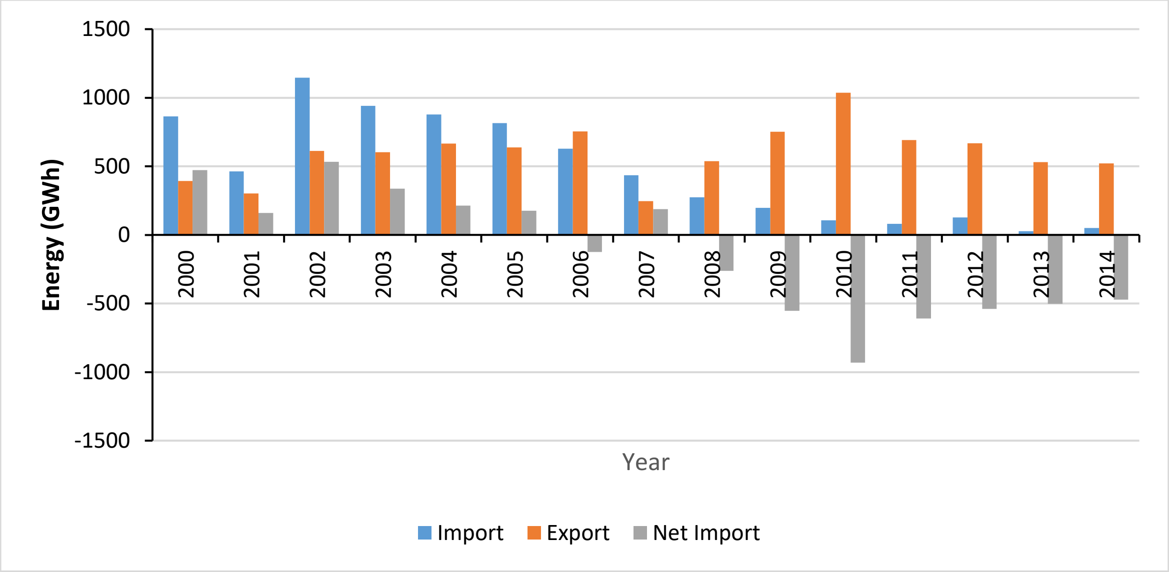

Figure 2.3: Imports, exports and net imports of electricity in Ghana from 2000 to 2014 (**Source:** Author's computation with information from Energy Commission (2014) and Energy Commission (2015c))

Figure 2.3 shows that Ghana imported more electricity than it exported in the years 2000 to 2005 and 2007. This could be the result of low level of domestic generation in these years. More electricity had to be imported to augment domestic generation to meet domestic demand. As such net imports for these years were positive. However, in the years 2006, 2008 and after, exports have exceeded imports yielding negative net imports of electricity. This could be due to the fact that Ghana has improved her electricity generation in the last few years with the building of another hydroelectric power station and additional thermal plants. The negative net imports could be sustained with a continuous addition of more generation capacity.

2.4 Electricity Market Structure in Ghana

The electricity sub-sector in Ghana can be categorised into four main phases, namely the generation, transmission, distribution and regulatory/monitoring (PSEC & GRIDCo, 2010). Within these four phases, there are key institutions responsible for each phase. Figure 2.4 illustrates the four phases in the electricity sub-sector and institutions that are responsible.

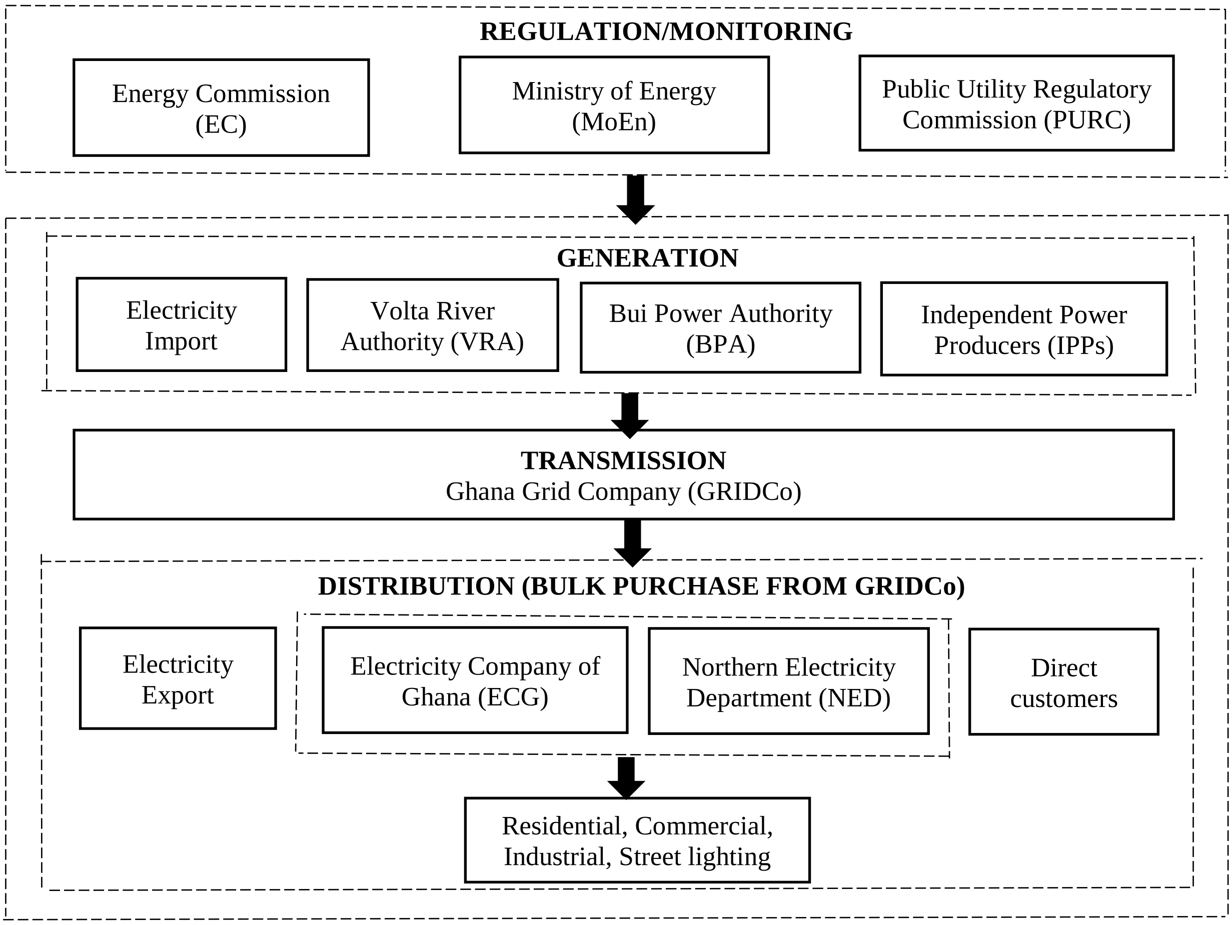

Figure 2.4: Current market structure of electricity sub-sector in Ghana (Source: Author's construct with information from Kapika and Eberhard (2015, page. 130)

2.4.1 Regulation and Monitoring

In terms of regulatory/monitory, three institutions have been handed regulatory mandates over electricity in Ghana. The first is the Ministry of Energy (MoEn), a statutory body that oversees all the institutions in the energy sector. The ministry is responsible for formulating, implementing, monitoring and evaluating policies regarding energy that includes electricity in Ghana (MoEn, 2016). Second is the EC established by an act of parliament Act 541 in 1977. The EC's foremost mandate is to provide the legal, regulatory and supervisory framework for providers of energy in Ghana that is issuance of licenses to all operators in the energy sector and the establishment and enforcement of standards of performance for both public and private utilities (Energy Commission, 2016). The third is the Public Utilities Regulatory Commission (PURC) an independent body also setup by an act of parliament, act 538 to regulate and oversee the provision of the highest quality of electricity and water services to consumers. Among the key functions of PURC are to provide guidelines for tariffs to be set for the provision of utility services as well as examining and approving of tariffs (PURC, 2016). The PURC also monitors and enforces standards of performance for the provision of utility services and protect the interest of consumers and providers of utility services (PURC, 2016).

2.4.2 Generation

As shown in Figure 2.4, there are three main institutions responsible for electric power generation in Ghana. Of these three, the VRA is the largest and most influential. Further, electricity is also imported from Cote D'Ivoire to supplement domestic generation. VRA was established in 1961 under the Volta River Development Act, act 46 of the Republic of Ghana with the primary function of generating and supplying electricity for industrial, commercial and domestic use in Ghana. VRA started generation of electricity from the Akosombo dam and later the Kpong dam. Additionally, VRA generates electricity from thermal facilities to augment hydro generation. It is worth noting that the third hydro dam that is the Bui dam is not operated by VRA but an institution called the Bui Power Authority that is also established by an Act. Private players have also joined in the generation of electricity and electricity is also imported into the country. Electricity generation has been opened for IPPs to join to increase generation capacity and to allow for competition.

In the year 2005, following the promulgation of major amendments to the VRA Act in the context of power sector reforms by the government of Ghana, VRA's mandate was revised and now focuses mainly on electricity generation. Its transmission functions have been separated into a distinct entity, the Ghana Grid Company (GRIDCo) to perform transmission activities.

2.4.3 Transmission

In the year 2005, following the amendments to the VRA Act within the framework of Power Sector Reforms, GRIDCo was established. GRIDCo is wholly own by government and it is responsible for the establishment and exclusive operation of the National Interconnected Transmission System. The company became fully operational in 2008 following the transfer of core staff and assets from VRA to GRIDCo. The company therefore transmits electricity generated in the country to bulk distribution companies for onward distribution of electricity to final consumers.

2.4.4 Distribution

The ECG and the NED (a subsidiary of the VRA) are the main institutions responsible for the distribution of electricity to final consumers in Ghana. Until 1987, the responsibility for distributing electricity in the country rested solely on the ECG. The NED was created as a subsidiary of VRA and took over from the ECG, the responsibility of running and developing electric power distribution system for the Brong Ahafo, Northern, Upper East and Upper West regions. ECG therefore now focuses on distributing electricity to the southern part of Ghana comprising the Greater Accra, Volta, Central, Western, Eastern and Ashanti regions. As part of electricity distribution, there are also direct customers as well as electricity export. Direct customers are a segment of large load customers served directly from the power producers (VRA, BPA and IPPs) without going through distribution companies (i.e. ECG and NED). They include VALCO, Export Free Zone, Aluworks, Akosombo Textiles Ltd, VRA Township among others.

2.5 Summary

This chapter presented an overview of the past and current state of the electric power system in Ghana. The chapter gave the current facts and figures about generation system capacity, electricity generation, past electricity demand, imports and exports of electric power. It came to the fore that electricity in Ghana is generated through two main sources namely; hydro and thermal. The installed capacity and dependable capacity from all sources of electricity generation in Ghana was collated. It was revealed that at present thermal generation capacity share is much higher than hydro due to the addition of more thermal plants over the years. In terms of electricity generation, hydro sources have contributed more to electricity generation than thermal sources in the past fifteen years. However, the contribution of thermal sources to electricity generation has seen a steady increase in the same period due to the addition of more thermal plants. The chapter ended by discussing the electricity market structure and the institutions responsible for the electricity sub-sector in Ghana. The electricity market structure in Ghana has been divided into four phases and this study focuses on the generation phase (see Figure 2.4).

CHAPTER THREE

REVIEW OF LITERATURE

3.1 Introduction

In this chapter, we give a review of the literature in the study area in order to put the current study into context. The chapter first gives a brief discussion of capacity expansion planning and focuses on electricity GEP. Furthermore, various methodologies for GEP problems and stochastic GEP research are discussed. Subsequently, a brief review of the field of stochastic optimization, the methodology adopted for our GEP problem, is done. The literature review continues with a brief description of the various methodologies for generating scenarios for stochastic parameters. Finally, the solution methods for solving stochastic optimization are described.

3.2 Capacity Expansion Planning

Capacity expansion do arise under a wide range of applications as a crucial part of strategic level decision making (Taghavi & Huang, 2014). Examples include heavy process industries (MirHassani & Noori, 2011; Peng, Erhun, Hertzler, & Kempf, 2012), electric utilities (Ravadanegh & Roshanagh, 2014; Zhu, Li, & Huang, 2013), telecommunication networks (Inoue, Kimura, & Ueda, 1994; Lee, 2000), automobile industries (Volling, Matzke, Grunewald, & Spengler, 2013), service industries (Berman, Ganz, & Wagner, 1994; Chao, Chen, & Zheng, 2008) among others. In all of these applications, the expansion of production capacity usually involves huge capital investment, as well as uncertainties over long periods of time making these decision problems very complex (Ahmed & King, 2000; Taghavi & Huang, 2014). As a result, quantitative models for economic capacity expansion planning have been the subject of intense research for the past decades. Four questions must be answered when the study of capacity expansion planning is done (Buehring, Huber, & Marques, 1984).

1 What type of capacities will be added to the system?

2 How much capacities will be added?

3 When will these capacities be added?

4 Where will these capacities be located?

The first three questions are what this thesis intends to answer in the GEP problem. However, for the question of where to locate the new facilities a detailed feasibility study has to be carried out considering load centres, availability of fuel, water, transmission corridors and so forth and is beyond this work.

3.3 Generation Expansion Planning

Electricity systems, as well as other systems, require decision makers to be careful when planning additional capacity (Kothari & Kroese, 2009). The planning process, in the case of electric power system has some anomalies that make decision making complex. This is because generation facilities for example require big investments that spread over long-term horizon (Gu, 2011). Moreover, electricity is an absolute essential commodity which requires a significant regulator vigilance (Bukari, 2012). Finally, electricity demand tends to fluctuate and must be exactly and instantly supplied by generation while electricity cannot be stored (Jin, 2009).

Planning for electric power generation expansion or simply put GEP is the process of determining the *technology type, timing* and *number of units* of generators to be added to an existing system and where they should be constructed to meet growing electric power demand over a long-term horizon (Li, Coit, Selcuklu, & Felder, 2014). Majority of studies focus on minimizing the cost, however, GEP includes many other objectives such as environmental impacts of generation or profit and so on. There are also some studies that solved multi-objective versions of the problem (Tekiner, Coit, & Felder, 2012). Moreover, expansion plan is developed according to the estimates about the future, and this yields many uncertainties in the system. Therefore, there are some studies done to consider the stochastic characteristics of the GEP problem (Li et al., 2014; Rebennack, 2014). Besides the studies which consider different aspects of the problems, there are also many methods that have been used to solve the problem and methods for generating scenarios (Kaut & Wallace, 2003) to represent the uncertainties (Ahmed & Sahinidis, 2003; Freund, 2004).

The study of GEP is very important because new generation capacity cannot be added overnight. It takes time and a huge financial investment to construct a new electric power plant, and once it is installed, it will be there for many years (García-bertrand, Kirschen, & Conejo, 2008). Therefore, it needs suitable planning to arrange the generation expansion process in advance, determine the right technology types, the proper capacity sizes and the right time to construct new electric power plants. On the one hand, if the required total generation capacity in the future is underestimated, then supply security will be compromised in the future. On the other hand, if it is overestimated, a huge amount of funds will be wasted to build the expensive but needless electric power plants.

Based on the system, adding new generation capacity can be done by either a regulatory authority (centralized planner) or independent power producers (IPPs). On the one hand, centralized system responsibility for generation expansion decisions devolves upon a regulatory authority that makes decisions based on cost and reliability (ensure enough electric power is available with a reasonable reserve margin) (Sharma, 2009). This framework usually corresponds to traditional electric power systems. On the other hand, in deregulated system, IPPs undertake the setup on new generation units at their own risks, while the regulatory authority only plays a supervisory role. The major objective of IPPs is obtaining the maximum profit but they also follow strategic objectives (generation technology mix). This schema is nowadays followed in most developed countries all over the world (Sharma, 2009).

3.3.1 GEP Problem Formulation

The GEP problem starts with an existing electric power network. This existing network consists of large central or distributed generation units (Tekiner, 2010; Tekiner, Coit, & Felder, 2012). Electricity generated in the generation units are transmitted to area grid by transmission lines. Demand is represented by load centres (stations) and distribution lines are used to distribute electricity to consumers. As the electricity demand keeps increasing, the existing network will be insufficient in the future. Therefore, the existing system should be expanded using new technologies in order to provide economic and reliable energy supply in the future (Tekiner, 2010). An expansion schedule is determined by solving the GEP problem as an optimization problem for a long-term planning horizon.

There are three main electricity capacity expansion methods that can be carried out namely generation expansion, transmission expansion and distribution expansion (Faleye, 2012). The literature review presented in this study focuses on the studies where generation expansion is the main objective. A generation expansion plan can include both building large central generation units such as large hydro generation units, nuclear generation units, coal burning generation units, thermal generation units, etc. and small distributed generation units close to consumers (Tekiner, 2010). Figure 3.1 presents the optimization model formulation for the GEP problem (Tekiner, 2010).

Optimization model formulation for GEP

Decision variables

- Number of large Central Generation Units
- Number of Renewable Generation units
- Number of Distributed Generation Units
- Amount of energy (MWh or GWh) produced by generation units

Objective function

Minimize

- Capital investment cost
- Fixed operation and maintenance (O&M) cost
- Variable operation and maintenance (O&M) cost
- Cost of unserved energy
- Electricity import cost
- Carbon emission cost

Subject to constraints

- Demand balance constraints
- Capacity constraints
- Reliability constraints
- Carbon emissions constraints

Figure 3.1: Optimization model formulation for GEP problem (Source: Author's own construct with information from Tekiner (2010))

From Figure 3.1, decision variables for the optimization model are the number of types of generation units to build and the capacity of the units as well as the amount of energy produced by the generation units. The objective is to minimize total cost of investment while meeting a number of physical and social constraints. The constraints are the energy balance constraints, generation constraints, reliability constraints etc. In addition, there are a number of stochastic parameters such as demand growth rate, fuel price, environmental or government regulation that can be part of GEP problem which makes the optimization problem stochastic in nature (Tekiner, 2010; Tekiner, Coit, & Felder, 2012).

3.3.2 Reliability Indices for GEP

The reliability of a system is defined as the ability of the system or component to perform its required functions under normal conditions for specified period of time (Billinton & Allan, 1994; Russell & Taylor, 2011, page. 163). Indices often used to represent the reliability of the electric power system are loss of load probability, loss of load expectation and expected energy not supplied or loss of expected energy (Billinton & Allan, 1994). A loss of load occurs when the system load level or demand level, exceeds the available generation capacity in the system. Loss of load probability is defined as the probability that there is a loss load. Loss of load expectation is defined as the expected number of time units in a specified period in which demand exceeds the available capacity. Expected energy not supplied or loss of expected energy is defined as the expected amount of unserved energy in a period. A more detailed explanation of these indices can be found in Billinton and Allan (1994).

Moreover, reliability of the electric power system can be assessed in terms of cost of unserved energy (Khan, Yingyun, Ashfaq, & Malik, 2014; Malik & Kuba, 2013). This cost is basically the cost to the economy due to unreliable electric power supply. When more capacity is added in the system, the investment cost would be high but because of more capacity in the system the cost of unserved energy would be low as the system would be more reliable (Malik & Kuba, 2013). On the other hand, if the capacity added is less than the actual required, then there would be more unserved energy and hence higher cost of unserved energy (Billinton & Allan, 1994; Malik & Kuba, 2013). The idea of reliability-cost or reliability-worth evaluation as illustrated in Malik and Kuba (2013) is shown in Figure 3.2.

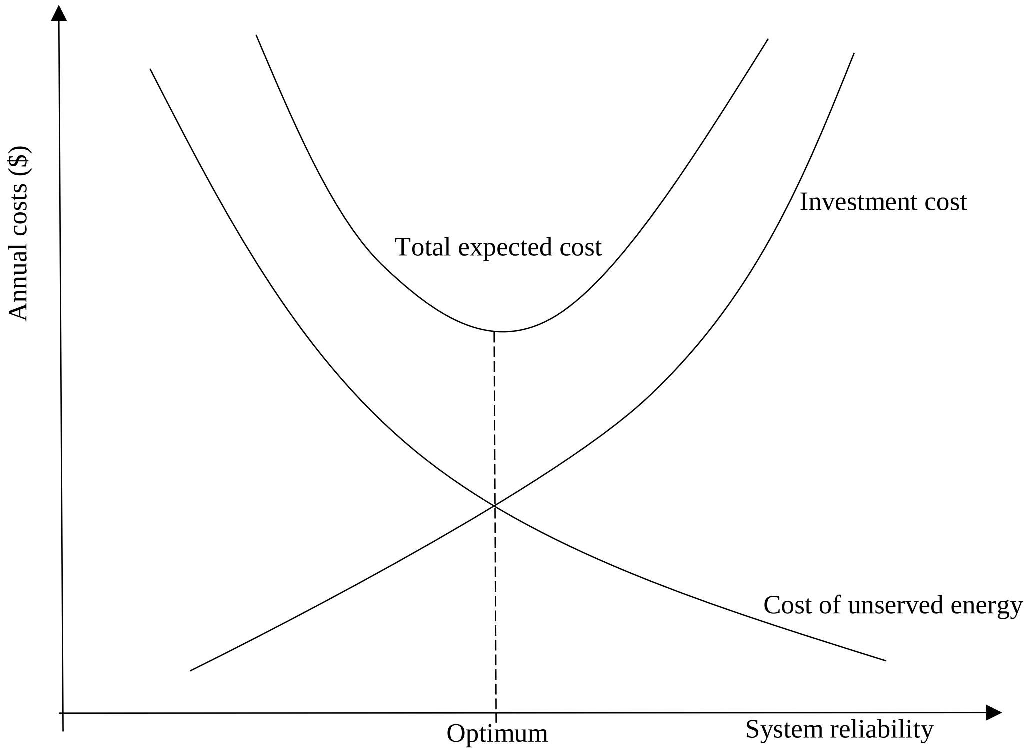

Figure 3.2: Relation between cost of unserved energy, investment cost and total expected cost with respect to reliability (**Source:** Malik & Kuba (2013))

Figure 3.2 shows that the investment cost generally increases with higher reliability, that is, capital investment is augmented in order to improve the reliability. On the other hand, the cost of unserved energy decreases as the reliability increases. The total expected cost is the sum of the investment cost and the cost of unserved energy. In our model in Chapter 5, reliability is embedded in terms of cost of unserved energy.

3.3.3 Methodologies Applied to GEP Problem

The GEP problem has existed for some decades now. Over the decades, attempts have been made to apply different optimization techniques to study the problem with researchers concentrating on different aspects of it. This section presents a summary of the different optimization techniques applied to the GEP problem.

Kagiannas, Askounis and Psarras (2004), Zhu and Chow (1997) and Hobbs (1995) give a review of optimization techniques applied to GEP. These authors have provided a detailed list of previous studies using dynamic programming approaches, decomposition techniques, stochastic programming, genetic algorithm, fuzzy set theory, analytic hierarchy process, artificial neural networks, network flows, simulation annealing and so on. Furthermore, Sahinidis (2004) provides the state-of-the-art survey on optimization techniques applied to GEP problem under uncertainty. The author's review saw a number of optimization techniques including stochastic programming, robust stochastic programming, chance-constraint (probabilistic) programming, stochastic dynamic programming and fuzzy programming.

Besides, a game-theoretic model was applied to the GEP problem to solve the problem in a deregulated competitive market environment to learn the different results from the regulated market environment (Mulvey, Vanderbei, & Zenios, 1995). Voropai and Ivanova (2002) and Chuang, Wu and Varaiya (2001) proposed a multi-objective technique which can also be applied to the GEP problem to minimize cost, fuel price risks and environmental impact. The multi-objective technique has been applied in Tekiner (2010).

3.4 Stochastic Optimization

An optimization problem, also known as mathematical programming problem is the selection of best decisions to achieve an optimal goal, subject to various constraints (Shapiro & Philpott, 2007). If all parameters are known with certainty before making the optimal decision, it is a deterministic optimization problem. However, if some of the parameters are not known in advanced, the problem becomes a stochastic optimization problem (Birge & Louveaux, 1997; Kall & Mayer, 2005.; Shapiro & Philpott, 2007). Although, mathematical programming in its deterministic form is highly recognized and widely used, uncertainty can only be handled by sensitivity or parametric analysis. Stochastic optimization overcomes this drawback by including uncertainty explicitly into mathematical programming.

Stochastic optimization is understood as a technique for modelling optimization problems involving uncertainty (Wallace, 2003). In particular, stochastic optimization takes the deterministic optimization problem and expands it to multiple realizations of the stochastic parameter, where each realization corresponds to a scenario from a set of scenarios (Gandulfo & Gil, 2014). Thus, stochastic optimization requires representing the probability distribution of the stochastic parameters by a finite set of discrete scenarios (Birge & Louveaux, 1997). In this sense, stochastic optimization is capable of finding a unique solution that is feasible for all scenarios and that is optimal in some sense and minimizes/maximizes the expected value of a certain objective function.

There are two classes of stochastic programming models - two-stage stochastic programming and multi-stage/multi-period stochastic programming. This study employs the later for the GEP problem in Ghana.

3.4.1 Two-stage Stochastic Programming

The most basic and widely applied stochastic optimization model is two-stage stochastic programming, which was first studied by Dantzig (1955). The idea of a two-stage stochastic programming is that optimal decisions are based on data available at the time the decisions are made and not dependent on future observations (Shapiro & Philpott, 2007). This means that two-stage stochastic programming is static in the sense that we make (supposedly optimal) a decision at one point in time, while accounting for possible recourse actions after all uncertainty has been resolved. In this way, the decisions are partitioned into two stages according to the information flow and refer to as first-stage and second-stage decisions. It should be noted that the partitioning of decisions need not actually reflect the separation of main decisions and recourse actions but may simply reflect the timing of the decisions such that first-stage decisions are to be made immediately, whereas second-stage decisions can be delayed (Kall & Mayer, 2011).

3.4.2 Multi-period Stochastic Programming

In contrast to two-stage stochastic programming, which treat uncertainty statically (only once), multi-period stochastic programming problems attempt to capture the dynamics of unfolding uncertainties over time and adjust decisions dynamically (Huang & Ahmed, 2009). This means that decisions are made sequentially at certain periods of time based on the information available at each time period. When information is updated, decision makers can adjust their decisions based on the current states of the system and future uncertainties. The main benefit of using multi-stage models is that the interaction between decision making and uncertainty unfolding is represented more accurately and realistically (Li, Huang, Li, Xu, & Chen, 2010).

The multi-period stochastic programming can be viewed as an extension of two-stage stochastic programming to a multi-period setting. Like two-stage stochastic programming, decisions are made without anticipating future realizations of uncertain data, which forces a partitioning of decisions into stages (first stage and second stage decisions) according to the information flow. The realization of uncertain data is, however, only gradually revealed and decisions are therefore made dynamically.

3.5 Scenario Generation Methodologies

As an important part of a stochastic optimization model, this section is dedicated to scenario generation methods. The aim is to put into perspective the method used for scenario generation in Chapter 4 with the existing literature on the topic. The task of generating the scenarios that serve as input to stochastic optimization model can be handled in many ways, depending on the availability of information and data (Kaut & Wallace, 2003).

There are scenario generation methods that are based on experts' opinions or data manipulation. Application specific methods for generating scenarios this way, are not necessarily theoretically founded but may rely on subjective judgement, experts' opinion or data manipulation. A method, based simply on use of historical data, is presented in Nowak and Römisch (2000) who developed a multi-stage stochastic programming problem for GEP under electricity demand uncertainty.

Further, there are methods that aim to represent the probability distribution by matching statistical properties (Høyland & Wallace, 2001). The concept is to generate a discrete approximation such that certain statistical properties of the approximation match statistical properties calculated from data. Høyland, Kaut and Wallace (2003) present a scenario generation method called moment matching that matches specific statistical properties. The basic idea of the moment matching method is to minimize the distance between computed and specified statistical specifications (Høyland et al., 2003). The moment matching method has been used for stochastic optimization applications to electric power systems in the papers of Feng and Ryan (2013) and Fleten & Pettersen (2005).

Moreover, there are methods that approximate the specific probability distribution by sampling from a statistical model. This approach is the most common method for scenario generation (Breeden & Ingram, 2010; Vithayasrichareon, MacGill, & Wen, 2009; Vithayasrichareon & MacGill, 2012) and is employed in this thesis in generating scenarios for the stochastic parameter. With enough historical data, it may be possible to represent the probability distribution by a statistical model that is suitable for sampling. The modelling of the probability distribution can be done by the use of time series analysis and advanced stochastic processes such as regressions, autoregressive and moving average processes etc. (Kristoffersen, 2007). Note that if there is lack of data, regression may not always be possible and an alternative is autoregressive or moving average processes (Kristoffersen, 2007). To derive a discrete approximation of the probability distribution, sampling is employed. The most basic sampling procedure is the Monte Carlo sampling (Gentle, 2003) in which samples are all assigned the same probabilities (Raeside, 1976). The Monte Carlo sampling procedure has been applied in Shapiro (2003) who extended the procedure to a conditional sampling procedure suitable for multi-stage stochastic programming problems.

3.6 Solution Approaches to Stochastic Linear Programmes

Sometimes, the computational size of stochastic programmes such as the long-term GEP problem considered in this thesis can be huge. In addition, if integer decision variables are involved, it can be computationally difficult to solve. Thus, many researches have proposed alternative heuristic or other techniques to efficiently solve the problem.

These solution approaches to stochastic programming problems often divide into primal and dual decomposition methods (Kristoffersen, 2007). Primal methods aim at decomposing a problem according to stages, whereas dual methods decompose with respect to scenarios (Kristoffersen, 2007). We discuss some major contributions within solution approaches to multi-stage stochastic programs.

The authors, Ahmed, King and Parija (2003) gave a multistage stochastic programming method, recommended a reformulation technique and applied different heuristic techniques to solve the problem in a more efficient way. Fukuyama and Chiang (1996) used genetic algorithm to reduce the complexity encountered in the GEP problem. A comparison among a number of meta-heuristic techniques for solving the generation capacity expansion problem was studied in Firmo and Legey (2002). Ahmed and Sahinidis (2003) developed a fast-linear programming based approximation scheme that efficiently solves a multistage stochastic integer programme arising from a capacity expansion planning problem. Computational effort for solving capacity expansion planning problems by two stage stochastic programming was studied by using Benders decomposition and parallel algorithm (Malcolm & Zenio , 1994). Benders decomposition technique was first published by Benders (1962) and then Geoffrion (1972) reviewed the method. Freund (2004) describes how to apply Benders decomposition for structured optimization problems under uncertainty.

3.7 Summary

The chapter reviewed literature on capacity expansion planning with particular focus on GEP. The GEP problem was treated as typical optimization problem and many optimization methods have been applied to it in the literature. Reviewing the various optimization techniques applied to the GEP problem, it came to the fore that stochastic optimization model which was employed in this study was mostly used and has been proven to provide superior performance than other techniques when uncertainties in model parameters such as electricity demand exist. Further, a search into the literature revealed that most of the optimization models developed for solving the GEP problem assume the availability of sufficient funds for financing new capacities. However, assuming sufficient funds availability, especially for a developing country may lead to inapplicability of the expansion plan because it is almost certain sufficient funds will not be available. This thesis therefore proposes a new long-term stochastic MILP model for the analysis of capacity expansion plans under periodic budget constraints. The proposed stochastic MILP model with periodic budget constraint, also allows for unused budget allocation from previous periods to be saved and invested for use in subsequent periods. This approach is novel, and a contribution to literature on capacity expansion planning modelling for a developing country.

CHAPTER FOUR

METHODOLOGY

4.1 Introduction

This chapter presents the proposed stochastic optimization model formulation for a developing country that takes into account budget constraint. The model assumptions and notations upon which the capacity expansion problem is built are summarised in Section 4.2. Following this, the proposed stochastic MILP model formulation is presented in Section 4.3. The section after the model formulation discusses the parameters used as input in the stochastic MILP model. The chapter ends with a discussion on the software employed in solving the model.

4.2 Model Assumptions and Notations

To help place into context the proposed stochastic MILP model, specific model assumptions are outlined below:

1 The study assumes a regulated authority (centralized planner) in charge of the capacity expansion problem (even though some of the existing and proposed generators are owned by IPPs). This assumption is justified since the Ghanaian electricity market is still operated as such.

2 Planning for generation capacity is usually characterized by a number of uncertainties making it a very complex process. The study assumes annual electricity demand as the only uncertain parameter.

3 Adequate transmission and distribution resources are assumed to be in place to transmit the electric power generated by the new generators to be built. This assumption basically implies that our planning decisions are not affected by transmission and distribution constraints.

4 There is an increasing concern on carbon (CO_2) emissions and global warming issues. But that is not the focus of this current study. Thus, emission quotas are ignored.

5 The study assumes that prior to the year 2016 (the base year for the study), there was no budget left and any leftover budget thereafter is invested at a return of 12% per year. This value 12%, is based on the discount rate used in the GGMP (Tractebel Engineering, 2011).

6 It is assumed that no generator (including existing ones) would be retired within the 20-year planning horizon and any generator can serve base and peak loads.

7 Only four hydropower plants can be constructed within the planning period. This conforms to the number of significant hydro opportunities in Ghana. However, there is no limit on the number of thermal and coal plants that can be built within the planning period.

Following, the notation of decision variables, scenario decision variables, parameters and scenario parameters for the stochastic MILP model are presented.

Indices

g	Index for generator type
t	Index for time period
s	Index for demand scenario

Decision Variables

$G_{t,g}$	Number of units of type g generator to be built starting in period t, integer
$Z_{t,g}$	Total new installed capacity of generator of type g at period t, MW
$W_{t,g}$	Total (new and existing) installed capacity of generator of type g available at the beginning of period t, MW
$Y_{t,s,g}$	Electric power generated by generator type g under scenario s in period t, MWh
$UE_{t,s}$	Total unserved energy under scenario s in period t, MWh
$IE_{t,s}$	Electricity import under scenario s in period t, MWh

Parameters

Av_g	Availability factor of generator type g, %
$n_{t,g}^{max}$	Maximum installed capacity of a new type g generator in period t, MW
Δ_g	Number of years to construct type g generator
I_g	Existing installed capacity of type g generator, MW
G_g^{max}	Number of generator type g that can be built over the entire planning period
K_t	Number of hours in period t
ρ_t	Proportion of energy demand in period t served through import, MWh
$C_{t,g}$	Levelized capital investment cost to build new generator of type g in period t, \$/MW/year
$C_{t,g}^{CC}$	Capital cost of generator of type g in period t, \$/MW
$f_{t,g}$	Levelized fixed O&M cost of generator of type g in period t, \$/MW/year

$\beta_{t,g}$	Variable O&M (including fuel cost) cost of generator type g in period t, \$/MWh
γ_t	Penalty cost for unserved energy in period t, \$/MWh
λ_t	Electricity import cost in period t, \$/MWh
B_t	Budget for meeting period t new additional capacity, \$
r	Annual interest rate for cost discounting, %

Scenario dependent parameters

$d_{t,s}$	Electricity demand under scenario s in period t, MWh
$B_{t,s}^{L}$	Total of past periods unused budget under scenario s in period t, \$
p_s	Probability that scenario s occurs

4.3 The Stochastic MILP Model Formulation

This section presents the stochastic optimization model for GEP for a developing country. The stochastic optimization model formulates future uncertainties as different discrete scenarios (Jin, 2009). There are two types of decision variables in this formulation. The investment decision variables, $G_{t,g}$, $W_{t,g}$ and $Z_{t,g}$, referred to as the first stage decision variables, since they have to be decided on at the beginning of each period before the outcomes of any future uncertainties are revealed. On the other hand, operational decision variables, $Y_{t,s,g}$, $UE_{t,s}$ and $IE_{t,s}$ are scenario dependent, which are referred to as second stage decision variables, since their decision can be deferred until after the realization of some uncertain scenario described by the scenario parameter, $d_{t,s}$. A uniform probability value, p_s, aggregating to 1 over all scenarios, is assigned to each scenario. The objective is to minimize the present value of the total expected cost over the planning period and over scenarios subject to series of constraints that must be satisfied for every scenario.

Following the notations in Section 4.2, the proposed multi-period stochastic MILP model formulation is as follows:

$$\text{Minimize} \quad \sum_t \left(\frac{\sum_g (C_{t,g}+f_{t,g})Z_{t,g}+\sum_s p_s\left(\sum_g \beta_{t,g}Y_{t,s,g}+\gamma_t UE_{t,s}+\lambda_t IE_{t,s}\right)}{(1+r)^{t-1}}\right) \tag{4.1}$$

Subject to:

$$\sum_g C_{t,g}^{CC} n_{t,g}^{max} G_{t,g} + \lambda_t IE_{t,s} \le B_t + (1+r)\, B_{t-1,s}^{L} \quad \forall t, \forall s \tag{4.2}$$

$$B_{t,s}^{L} = B_t + (1+r)B_{t-1,s}^{L} - \sum_g C_{t,g}^{CC} n_{t,g}^{max} G_{t,g} - \lambda_t IE_{t,s} \quad \forall t, \forall s \tag{4.3}$$

$$Z_{t,g} = Z_{t-1,g} + n_{t,g}^{max} G_{t-\Delta_g,g} \quad \forall t, \forall g \tag{4.4a}$$

$$W_{t,g} = I_g + Z_{t,g} \quad \forall t, \forall g \tag{4.4b}$$

$$\sum_t G_{t,g} \le G_g^{max} \quad \forall g \tag{4.5}$$

$$Y_{t,s,g} \le K_t A v_g W_{t,g} \quad \forall s, \forall g \tag{4.6}$$

$$\sum_g Y_{t,s,g} + IE_{t,s} = d_{t,s} - UE_{t,s} \quad \forall t, \forall s \tag{4.7}$$

$$IE_{t,s} \le \rho_t d_{t,s} \quad \forall t, \forall s \tag{4.8}$$

$$G_{t,g}, Z_{t,g}, W_{t,g}, Y_{t,s,g}, UE_{t,s}, IE_{t,s} \ge 0 \quad \forall g, \forall s, \forall t \tag{4.9}$$

The stochastic MILP model equations are describe as follow:

- *Objective function*: Equation (4.1) is the objective function for the multi-period stochastic MILP model. The objective function seeks to minimize the total expected cost of electricity provision over all possible scenarios in the entire planning horizon discounted to the present value. The first term which is a summation over the planning horizon, expresses the investment cost of additional generation capacity and comprises capital investment cost and fixed O&M cost. The second term is made up of the expected variable O&M cost, cost of unserved energy and electricity import cost.

- *Budget constraint:* Equation (4.2) represents the budget constraint. The budget constraint ensures that cost of financing new generation capacities and electricity import in any period t does not exceed the funds available in period t. Available funds in period t comprise of period t's budget allocation plus total of unused budget from the immediate past year which is assumed to have been invested at an interest rate of r% per period.

- *Unused budget constraint:* Equation (4.3) represents the unused budget. This gives the amount of unused budget from the immediate past year with the assumption that any unused budget is carried over to the next period.

- *Capacity installed constraints*: Equations (4.4a) and (4.4b) are the capacity installed constraints. Equation (4.4a) tracks the total new generation capacity of a generator type in a given period as additional capacity is added over time. Equation (4.4b) tracks the total available generation capacity (existing and new) of a generator type in a given period as additional capacity is added over time. Equation (4.4a) in particular, takes into account construction time for new generator types.

- *Maximum units of generator type to build constraint:* Equation (4.5) represents the maximum units of generator type to build constraint. This equation ensures that the number of units of new generator type to be built within the planning period should be less or equal to its maximum limit. For example, the number of hydro plants to be constructed within the planning period cannot exceed four hydro opportunities available to Ghana with roughly the same size range of an average of 60 MW.

- *Generation constraint:* The load generation for each type of generator type is represent by Equation (4.6). This equation ensures that the load generation of each type of generator g, should be less than or equal to its total capacity available at the beginning of period t.

- *Demand and supply balance constraint:* The demand and supply balance is represented by Equation (4.7). This ensures that the amount of electricity (i.e. generation by the available capacity of all generator types plus the amount of imported electricity) matches exactly the demand minus the amount of unserved energy in any period under any scenario. For simplicity, demand values include reserve capacity so that this need not be explicitly modelled in the optimization.

- *Maximum electricity import constraint:* Given that neighbouring countries also sometimes suffer power outages as a result of insufficient generation capacity, Equation (4.8) seeks to enforce the restriction that under any scenario of demand, the sum of all imported energy cannot exceed a certain percentage, ρ_t of the total energy demanded. For instance, this percentage is roughly 4% according to the GGMP (Tractebel Engineering, 2011)

- *Non-negativity constraint:* Equation (4.9) is the non-negativity constraint which ensures that the values of the decision variables are greater than or equal to zero.

The model above would be run for two cases. First, without considering the realistic case of budget constraint. Thus, we drop Equations (4.2) and (4.3). This will depict the case where there are always enough funds to undertake an expansion plan. Secondly, the model is enhanced to accommodate budget constraints. This case shall represent the case of Ghana as a developing country that is faced with budget deficit. Budget constraint in this study is equivalent to setting aside a percentage of the national GDP in each year solely for the financing of new generation capacities and electricity import.

4.4 The Model Parameters

The proposed stochastic GEP model is based on a number of parameters. These include technical and economic parameters of generation technology types, cost of unserved energy, discount rate and electricity import cost which are to be used as input data to the model. The other data set needed involves electricity demand forecast values, the only stochastic parameter in this study. Further, data on yearly budget allocation for capacity addition are needed. Budget constraint is represented by a portion of Ghana's projected future GDP for the 20-year planning horizon.

The source of data used in this study was secondary. The data were obtained from the GGMP (Tractebel Engineering, 2011) and other bodies that collect energy statistics in Ghana and beyond. The study used yearly electricity demand data from 2000 to 2014 which consist of the domestic demand, export and losses to estimate electricity demand scenarios. It should be mentioned here that many of the data used in this thesis are adapted from the GGMP (Tractebel Engineering, 2011). Note also that some of the data specific to the technologies considered in this work, such as costs data, although being of 2011 values, are generally within the close range of the currently reported figures.

4.4.1 Generation Technology Types

In this study, four types of generation technologies are considered for capacity addition namely; hydro, CCGT, OCGT and coal. These technologies were adapted from the GGMP (Tractebel Engineering, 2011) with various capacity sizes. In this thesis, we use two different capacity sizes for CCGT technology and called them CCGT1 and CCGT2 and the same is applied to coal that is coal1 and coal2. The installed capacity size for new generators are based on the recommendation in the GGMP (Tractebel Engineering, 2011). Note that the new install capacity size for hydro is an average of four available hydro opportunities in the country.

Other aspects of the generation technology types are availability factor, existing installed capacity and construction time which are important items in the planning process. The availability factor of a generating unit is the percentage of the time that it is available to produce energy to the power grid (Tidball, Bluestein, Rodriguez, & Knoke, 2010). The availability factor for technology options were obtained from the GGMP (Tractebel Engineering, 2011). For a robust and reliable GEP, we take into consideration the time required for the construction of the generators. The construction times used in this study are based on estimates obtained in GGMP (Tractebel Engineering, 2011). In fact, the total construction time of a project including feasibility studies varies from 2 years for a gas-fired plant (CCGT and OCGT) to 4 years for a coal-fired plant. Similarly, average construction time of a hydro plant is 4 years for the capacity size considered in this study. Finally, the operation time of the power plants is assumed to be 8760 hours in a year.

4.4.2 Costs of Power Generating Technologies

The costs (economic data) of power generating technologies can be divided into three categories: capital investment cost, fixed O&M cost and electricity generation cost (Jin, 2012).

The capital investment cost, expressed in \$/MW of installed capacity, is the capital outlay required to build a generator. This cost is expressed in annuity form for fairer selection of generation types in the objective function. By this approach, generators with high investment cost but low running cost are not unfairly overlooked for generators with low investment cost but high running cost. This approach also helps in avoiding running the model past the planning period in order to avoid sub-optimal decisions getting to the end of the planning horizon. As a result, the capital investment cost is levelized (expressed in \$/MW/year) so that the periodic equivalent is now used in the objective function.

The fixed O&M cost, expressed in \$/MW/year, is related to the expenditures for items used over an extended period of time and are independent of the amount of electricity generated by the plant. Finally, the electricity generation/production cost involves two parts: variable O&M cost and the fuel cost. Variable O&M cost, expressed in \$/MWh, vary directly with electricity production and includes all materials other than fuel consumed during operation of a power plant. On the other hand, fuel cost refers to those charges associated with consuming and owning fuel in an electric power plant. In this study, we added the fuel cost to the variable O&M cost. Note that hydro does not have fuel cost because it uses natural and renewable resources as fuel. All these costs are based on estimates in the GGMP (Tractebel Engineering, 2011).

4.4.3 Cost of unserved energy

Electric power outages can be destructive and costly. Hence, we impose a penalty for unserved energy. The cost of unserved energy is set at \$225 per MWh with a yearly escalation of 0.5%. There was no reliable technique in the literature for estimating cost of unserved energy. Therefore, the cost of unserved energy for Ghana was estimated by regressing annual domestic tax on electricity supply for the period 2003 to 2014. The cost of unserved energy used in this study could be argued against but this value is in close range with the values discussed in GGMP (Tractebel Engineering, 2011).

4.4.4 Electricity Import Cost

As mentioned earlier, Ghana has an agreement with La Cote d'Ivoire for electricity import as the need arises. As such, electricity import cost from neighbouring countries was required. There was lack of information on the electricity import cost due to confidentiality issues so the value used in this work is an estimate. The electricity import cost is set at $150 per MWh with a yearly escalation of 0.5%.

4.4.5 Discount Rate

The discount rate is used to determine the economic costs in the entire planning horizon. Thus, the discount rate is used to account for time value of money and to discount the annual expenditures to the present value in year 2016, which represents the initial year as well as the reference year. In this study, we assume the annual interest rate $r = 12\%$ as used in the GGMP (Tractebel Engineering, 2011).

4.4.6 Electricity Demand Scenario Generation

Electricity demand $d_{t,s}$ is the only uncertain parameter in the proposed stochastic MILP model and we needed to model this over the multiple years. The method used in generating scenarios for electricity demand was based on the Monte Carlo sampling approach of Breeden and Ingram (2010) as follows:

Let $d_{t,s}$ be period t's demand under scenario s. The electricity demand forecast for period $t+1$ under scenario s is determined according to Equation (4.10).

$$d_{t+1,s} = (1+\omega)d_{t,s} \qquad \forall t, \forall s \tag{4.10}$$

The symbol ω in Equation (4.10) denotes the expected percentage increase in demand over the current period's demand level and is treated as a random variable. Further, the ω was estimated to follow the triangular distribution, *Triang* (0.01,0.07,0.15) with a minimum increase of 1%, the most likely increase of 7% and a maximum increase of 15% per year. This distribution is reasonable given the lack of detailed and sufficient past demand data for estimating the distribution of ω. By this scenario generation approach, all the scenarios are assumed to have equal probability of occurrence.

The electricity demand for 2015 was used in Equation (4.10) to start the scenarios generation. As used in A. Afful-Dadzie, E. Afful-Dadzie, Awudu and Banuro (2017), the demand for 2015 was assumed to be equal to the national forecasted electricity demand of 17,716.9 GWh. This value for starting the scenario generation is considered appropriate because actual electricity supplied in 2014 was 1,3071 GWh (including losses) and 12% to 16% of energy demanded was not met (Energy Commission, 2015a). Also, a reserve capacity of 10% per available capacity was included in the 2015 forecasted demand.

4.4.7 Projected GDP for Budget Allocation

For the realistic case of budget constraint, the budget allocation is equivalent to the case of setting aside a percentage of the national GDP solely for the financing of new capacities and electricity import if the need arises. In that regard, the projected GDP for the 20-year planning period are required. In the year 2014, Ghana's GDP stood at \$38,620 million and 4% average

GDP growth rate was forecasted for the years ahead (World Bank, 2014). So, the projected GDP was based on the 2014 GDP assumed to grow at an average rate of 4% from 2016 to 2035.

4.5 Software Employed

Most optimization problems such as the GEP problem are large scale and require the use of special purpose software such as GAMS, AIMMS, AMPL etc. to solve them. These software have powerful solvers that allow for a large-scale optimization problem solution at a reasonable time. We opted to use GAMS with ILOG CPLEX 12.6.0.0 solver for our GEP problem because coding in GAMS is much easier and the software is readily available to us. It is worth noting however that AIMMS and AMPL have basically the same modelling capabilities of GAMS.

Sets

Declaration and assignment of members
e.g., {generators, period, scenarios etc.}

Data in the form of Parameters, Tables and Scalars

Declaration and assignment of values
e.g., {generator costs, ratings, line parameters, MW and MWh loads etc.}

Decision Variables

Declaration, assignment of type, bounds, initial values
e.g., {generation level, line flow, load bus voltages, tap setting etc.}

Equations

Declaration and definition
e.g., {cost function, generation limits on MW and MWh, load flow constraints, voltage limit etc.}

Model and Solve Statements

Declaration, assignment of appropriate solver
e.g., {Model GEP, Solve GEP Using MIP Minimizing Cost}

Output

Display
e.g., {display optimal generation level, line flows, voltage levels etc.}

Figure 4.1: Structure of a GAMS model (Source: Uchchkotiya et al., 2013)

The structure of an optimization model coded in GAMS has the components: sets, data, variables, equations, model and output as set out in Figure 4.1 (Uchchkotiya et al., 2013). In general, any optimization problem can be formulated in GAMS using these components. The data presentation in GAMS can be done in its most basic form using tables, columns etc. There are control statements (loop, while, if-else etc.) available which make GAMS flexible to use. There are output specifications like display which can generate reports in any required format. Also, the output can be directly linked to excel sheet programmes for graphical analysis etc. Debugging features exist for quick and effective errors identification. No attempt is made here to give the syntax of GAMS and the interested reader is referred to GAMS Users' Guide (Rosenthal, 2013) for such details.

CHAPTER FIVE

DATA PRESENTATION AND ANALYSIS OF RESULTS

5.1 Introduction

In this chapter, the proposed multi-period stochastic MILP model is implemented in the case of Ghana. The chapter first presents the study parameters, scenario assumptions for electricity demand and yearly projected GDP from 2016 to 2035. Following, the solution for the proposed stochastic GEP optimization model for the 20-year planning horizon, considering no budget constraint and with the realistic case of budget constraint, are presented and analysed. For the realistic case of budget constraint, various budget allocations analyses are made for policy direction.

5.2 The Study Parameters

5.2.1 Parameters Specific to the Generators

The parameters specific to the generator types and other parameters used in the proposed stochastic MILP model are summarised in Table 5.1.

Table 5.1: Parameters specific to generator types and other parameters

Parameters specific to generator types						
Generator type, g	**hydro**	**CCGT1**	**CCGT2**	**OCGT**	**coal1**	**coal2**
Existing capacity (MW), I_g	1580	1315	0	962.1	0	0
Investment capacity size (MW), $n_{t,g}^{max}$	60	300	450	150	125	250
Availability factor (%), Av_g	60	85	85	85	85	85
Construction time (years), Δ_g	4	2	2	2	4	4
Life span of generator (years)	60	25	25	25	35	35
Capital cost (\$/MW), $C_{t,g}^{CC}$	5000000	1057000	982000	639000	2976000	2559000
Fixed O&M cost (\$/MW/year), $f_{t,g}$	15000	34000	32000	6000	75000	65000
Variable O&M cost (\$/MWh), $\beta_{t,g}$	0.10	157.53	153.56	343.9	125.5	115.8
Other parameters						
Cost of unserved energy (\$/MWh), γ_t	225					
Electricity import cost (\$/MWh), λ_t	150					
Escalation of all costs, %	0.5					
Annual interest rate for discounting (%), r	12					
Number of hours in a year, k_t	8760					
Percent of electricity import (%), ρ_t	4					
Maximum number of hydro, G_{Hydro}^{max}	4					

Source: Tractebel Engineering (2011)

It would be observed that, coal1 and coal2 have no existing capacity. This is because Ghana currently does not operate coal powered plants. Also, CCGT2 has no existing capacity because the total existing capacity for CCGT technology has been assigned to CCGT1. For the availability factor, hydro is less available due to uncertain environment. Note that hydro is the most expensive in capital investment. However, in terms of operation cost, hydro is the most economical. Furthermore, hydro does not have fuel cost because it uses natural and renewable resources as fuel. Although the capital investment cost for hydro is very high, the much lower operation cost helps save more cost in the future years. Gas-fired power plants (CCGT and OCGT) have higher operation costs but shorter construction time while hydro and coal-fired power plants have lower running costs but longer construction times.

5.2.2 Electricity Demand Scenarios

Table 5.2 presents a portion (from 2016 to 2023) of six scenarios of annual electricity demand, $d_{t,s}$ forecast for Ghana based on the assumed triangular distribution. The results are based on Equation (4.10) using 2015 as the base year. Note that 20 scenarios were generated (see Appendix A) in each year and labelled as scen-1 to scen-20.

Table 5.2: Six selected scenarios of total electricity demand (in GWh) forecast of Ghana from 2016 to 2023 compared to the Ghana national demand forecast

	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
scen-3	18745.14	19955.83	21122.28	23622.45	26609.56	28364.53	29969.67	31329.56
scen-4	19717.49	21336.51	23081.62	24646.77	25574.58	27538.65	29942.02	33294.90
scen-8	18338.65	19848.25	21169.22	23731.17	24678.06	27481.63	29713.46	31558.05
scen-10	18577.35	20182.08	22039.98	23819.22	26093.34	27281.09	29959.45	31450.07
scen-18	19592.99	21126.90	23036.30	24041.38	25359.85	25989.87	28599.92	31334.10
scen-19	19870.87	22162.33	25082.85	27636.12	29474.03	32359.69	36572.65	38580.42
National demand Forecast	*19696.10*	*21040.70*	*22304.10*	*23573.70*	*24953.40*	*26424.90*	*27892.90*	*29481.70*

Source: Research data (2016)

It can be observed that the electricity demand scenarios are quite comparable to the national demand forecast. However, the scenarios are more reflective of the uncertainty in future demand and as shown in Table 5.2, the actual demand could be up or below the national average forecast. One of the documented strengths of stochastic optimization model is its ability to derive a solution that performs better than the solution from an average parameter such as the national average demand forecast.

5.2.3 Ghana's GDP Projection

As mentioned earlier, we consider budget constraint in the proposed stochastic MILP model. The periodic budget allocation values for the case study are determined as a percentage of the national GDP. In Table 5.3, the projected national GDP that are used to calculate yearly budget allocation and budget allocation scenarios from 0.25% to 3% of projected GDP are shown. Note that 2016 is the base year. Subsequent projected GDPs are computed by multiplying the previous year's projected GDP by 1.04.

Table 5.3: Projected GDP of Ghana and budget allocations as percent of GDP, million$

Year	Projected GDP	0.25% of GDP	0.5% of GDP	0.75% of GDP	1% of GDP	1.25% of GDP	1.5% of GDP	3% of GDP
2016	41771.39	104.43	208.86	313.29	417.71	522.14	626.57	1253.14
2017	43442.25	108.61	217.21	325.82	434.42	543.03	651.63	1303.27
2018	45179.94	112.95	225.90	338.85	451.80	564.75	677.70	1355.40
2019	46987.14	117.47	234.94	352.40	469.87	587.34	704.81	1409.61
2020	48866.62	122.17	244.33	366.50	488.67	610.83	733.00	1466.00
2021	50821.29	127.05	254.11	381.16	508.21	635.27	762.32	1524.64
2022	52854.14	132.14	264.27	396.41	528.54	660.68	792.81	1585.62
2023	54968.30	137.42	274.84	412.26	549.68	687.10	824.52	1649.05
2024	57167.03	142.92	285.84	428.75	571.67	714.59	857.51	1715.01
2025	59453.72	148.63	297.27	445.90	594.54	743.17	891.81	1783.61
2026	61831.86	154.58	309.16	463.74	618.32	772.90	927.48	1854.96
2027	64305.14	160.76	321.53	482.29	643.05	803.81	964.58	1929.15
2028	66877.34	167.19	334.39	501.58	668.77	835.97	1003.16	2006.32
2029	69552.44	173.88	347.76	521.64	695.52	869.41	1043.29	2086.57
2030	72334.54	180.84	361.67	542.51	723.35	904.18	1085.02	2170.04
2031	75227.92	188.07	376.14	564.21	752.28	940.35	1128.42	2256.84
2032	78237.03	195.59	391.19	586.78	782.37	977.96	1173.56	2347.11
2033	81366.52	203.42	406.83	610.25	813.67	1017.08	1220.50	2441.00
2034	84621.18	211.55	423.11	634.66	846.21	1057.76	1269.32	2538.64
2035	88006.02	220.02	440.03	660.05	880.06	1100.08	1320.09	2640.18

Source: Research data (2016)

5.3 Result

5.3.1 Result of the Case of Ghana

This section presents results for the proposed stochastic GEP model considering the case with no budget constraint and with budget constraint. As stated earlier, no budget constraint results are based on the premise of the availability of sufficient funds for financing the needed generation capacity to meet all future demands. The budget constraint results on the other hand, represent the reality in Ghana as a developing country that is faced with insufficient funds to finance the needed generation capacity. In the case of budget constraint, various budget allocations were considered (see Table 5.3).

5.3.1.1 The Case with no Budget Constraint

The expansion plan with no budget constraint that is assuming availability of sufficient funds for financing the needed generation capacity to meet future electricity demand, is shown in Table 5.4.

Table 5.4: Expansion plan with no budget constraint

Plant type	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Hydro	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	9	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	0	0	0	0

Source: Research data (2016)

It would be observed that, all 4 units of hydro, 1 unit of CCGT1, 1 unit of CCGT2 and 9 units of coal2 are suggested in year 2016 to be constructed. However, in year 2017 and thereafter only coal2 is suggested for construction. This is because hydro and coal2 appear to have lower running costs (variable O&M cost) that help save cost in future years (see Table 5.1). CCGT1 and CCGT2 seems to be high cost generators but are suggested in year 2016 because they have a shorter construction time and higher capacity credit than hydro and coal2 that can help serve the demand during the time that hydro and coal2 (which have longer construction time) are being constructed. No hydropower plant is recommended after 2016 because the maximum of four hydropower plants allowed within the planning period are recommended in 2016.

The cumulative installed capacity based on this expansion plan taking into account the time required to construct these units are shown in Table 5.5. Note that the years in Table 5.4 relate to the year when construction begins and the years in Table 5.5 relate to end of construction period (the year when a new capacity becomes available).

Table 5.5: Cumulative installed capacity (new) for no budget constraint

Year	Installed Capacity (MW)
2016	0
2017	0
2018	750
2019	750
2020	3240
2021	3490
2022	3740
2023	3990
2024	4240
2025	4490
2026	4740
2027	5240
2028	5740
2029	6240
2030	6740
2031	7240
2032	7740
2033	8240
2034	8990
2035	9740

Source: Research data (2016)

As shown in Table 5.5, the 1 unit of CCGT1 and 1 unit of CCGT2 suggested in year 2016 will be first to come on board in year 2018 with 300 MW (1x300 MW) and 450 MW (1x450 MW) additional capacity respectively. In year 2019, no capacity will be added and in year 2020 the 4 units of Hydro and the 9 units of Coal2 added 240 MW (4x60 MW) and 2,250 MW (9x250 MW) respectively given a cumulative installed capacity of 2,940 MW by year 2020. At the end of the planning horizon (in year 2035), 9,740 MW total new capacity would be installed. Note that Table 5.5 shows cumulative installed capacity for new generation capacity. To obtain the total available installed capacity (existing and new) in each year simply add total existing installed capacity of 3,857.10 MW to each value in Table 5.5. Note that 3,857.10 MW is obtained from the first row in Table 5.1.

5.3.1.2 The Case with Budget Constraint

In this case, the available budget set aside in each year for generation expansion is varied over a range of 0.25% to 3% of the projected national GDP. The budget allocation is varied to help the central planner foresee the consequences of his action and also to access the worthiness of increasing the budget allocation. Having solved the problem with the realistic case of budget constraint considering various budget allocations, the results obtained are summarised in Table 5.6. Note that the increase in budget allocation is 0.25% except from 1.5% to 3% of GDP which differ with an increment of 1.5%. The reason for moving from 1.5% to 3% was to observe the level of budget allocation that would be close to the expansion plan with no budget constraint.

Table 5.6: Expansion plans with various budget allocations

Plant type	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
									0.25% of GDP											
Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
CCGT2	0	0	0	1	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
									0.5% of GDP											
Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0
CCGT2	0	1	0	1	0	0	2	0	1	1	0	1	1	0	1	0	0	0	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75% of GDP																				
Hydro	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT2	0	1	1	1	0	1	1	1	0	2	1	1	1	1	1	1	1	1	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1% of GDP																				
Hydro	0	0	0	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT2	0	1	1	0	1	1	0	1	0	1	1	2	0	1	1	1	1	1	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
1.25% of GDP																				
Hydro	0	0	2	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT2	1	1	0	1	1	0	1	0	1	1	0	0	1	0	1	1	1	2	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	0	0	0	0	0	1	0	1	0	1	1	1	1	1	0	0	0	0	0	0
1.5% of GDP																				
Hydro	0	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT2	1	1	0	1	0	1	0	1	0	0	1	0	1	0	1	0	1	2	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	0	0	0	0	1	0	2	0	2	1	1	1	1	1	1	1	0	0	0	0
3% of GDP																				
Hydro	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCGT2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal2	1	1	1	2	2	2	2	2	3	2	3	2	3	2	3	3	2	0	0	0

Source: Research data (2016)

If 0.25% of GDP is allocated as budget, no generators are suggested for construction in year 2016. This is because prior to 2016 no funds were made available. However, in year 2019, some funds (year 2019 budget allocation plus the previous years' unused budget) were made available. But the funds made available are insufficient to finance the low running cost generators. To avoid incurring cost of unserved energy, 1 unit of CCGT2 is suggested in year 2019. This is because the central planner cannot wait till there is sufficient funds available to finance the high capital cost generators but with lower running cost. This is the dilemma developing countries face. Under tight budget constraint the central planner will resort to plants with lower capital cost but higher running cost. Because of this, CCGT2 might be optimal under the 0.25% of GDP budget allocation. However, a CCGT2 will be sub-optimal when the model does not impose budget constraint. The decision to go for a CCGT2 reflect the dilemma of waiting for sufficient funds to accumulate to finance least running cost generators and the incurring of high cost to the economy as a result of high levels of unserved demand. Similar observation can be made under a budget constraint of 0.5% of GDP.

When the budget is increased to 0.75% of GDP, 1 unit of hydro was suggested in year 2020. This is because there was sufficient fund at that point to construct Hydro which has a high capital cost but low running cost. If the budget is increase beyond 0.75% of GDP, more Hydro units are suggested and coal2 which is the next low running cost generator is suggested as can be seen in 1% of GDP and beyond. In addition, the expansion decision on coal2 tend to become even more attractive at 3% of GDP and CCGT1 and CCGT2 start becoming less attractive as the budget allocation increase. It is worth noting that when the budget allocation for a year is no longer able to cover the expensive capital investment cost of the plant types, electricity import becomes an option.

In Table 5.7, the cumulative installed capacity for each period comprising the new capacity addition based on the expansion planning decisions (see Table 5.6) taking into account construction time are shown.

Table 5.7: Cumulative new installed generation capacity for various budget allocations, MW

Year	0.25% of GDP	0.5% of GDP	0.75% of GDP	1% of GDP	1.25% of GDP	1.5% of GDP	3% of GDP
2016	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0
2018	0	0	0	300	450	450	450
2019	0	450	450	750	900	900	450
2020	0	450	900	1200	900	900	700
2021	450	900	1350	1200	1350	1410	1070
2022	450	900	1350	1650	1920	1530	1440
2023	450	900	1800	2160	1980	2040	1940
2024	900	1800	2310	2220	2430	2290	2440
2025	900	1800	2760	2670	2680	2740	2940
2026	900	2250	2760	2790	3190	3240	3440
2027	1350	2700	3660	3240	3890	3240	3940
2028	1350	2700	4110	3940	3890	4190	4690
2029	1800	3150	4560	4840	4140	4440	5190
2030	1800	3600	5010	4840	4840	5140	5940
2031	1800	3900	5460	5290	5090	5390	6440
2032	2250	4350	5910	5990	5790	6090	7190
2033	2550	4650	6360	6440	6490	6340	7690
2034	2550	4950	6810	6890	6940	7040	8440
2035	2550	4950	7260	7340	7840	8190	9190

Source: Research data (2016)

It would be observed from Table 5.7 that, as the yearly budget allocation increases, the installed capacity at the end of the planning horizon (2035) also increases. Note that cumulative new capacity addition for the various budget allocation follow the same principle as described in the expansion plan with no budget constraint.

5.3.1.3 Impact of Budget constraint

In this section, the level of unserved energy and its effect on budget constraint are studied. The benefit of studying the level of unserved energy is to give an idea as to whether it is worth to increase the budget allocation from say 0.25% to 0.5% of GDP. In Table 5.8 the percentage of average unserved demand for the no budget constraint and budget constraint in each year are shown. The percent average unserved energy is computed based on Equation (5.11) which is the expectation of the proportion of unserved energy sum over all scenarios s in period t.

$$\sum_s P_s \left(\frac{UE_{t,s}}{d_{t,s}}\right) \times 100 \qquad \forall t. \tag{5.11}$$

Table 5.8: Percent average unserved energy for no budget constraint and various budget allocations

Year	No budget constr	3% of GDP	1.5% of GDP	1.25% of GDP	1% of GDP	0.75% of GDP	0.5% of GDP	0.25% of GDP
2016	0.00	1.38	4.69	4.84	4.69	4.99	4.99	4.99
2017	0.00	8.38	11.12	12.01	11.75	12.17	12.17	12.17
2018	0.00	1.74	3.37	3.65	8.35	18.41	18.42	18.42
2019	0.00	6.60	0.59	0.59	1.92	10.19	10.20	24.23
2020	0.00	5.32	3.57	3.58	0.57	3.80	16.36	29.43
2021	0.00	3.14	0.90	1.17	2.89	1.17	9.85	22.01
2022	0.00	2.75	3.33	0.75	1.42	5.66	16.43	27.72
2023	0.00	0.97	1.26	1.53	0.71	2.54	21.78	32.35
2024	0.00	0.61	1.82	0.96	2.12	1.34	7.76	27.18
2025	0.00	0.37	1.50	1.71	1.65	1.26	13.49	31.90
2026	0.00	0.19	0.89	1.04	3.04	2.99	10.58	36.37
2027	0.00	0.00	2.07	0.30	2.73	0.74	9.49	33.30
2028	0.00	0.00	0.56	1.74	1.63	0.82	15.43	37.69
2029	0.00	0.00	0.97	2.43	0.33	0.82	14.36	35.08
2030	0.00	0.00	0.52	0.96	0.96	1.22	13.91	39.54
2031	0.00	0.00	0.77	1.89	1.09	1.23	14.98	43.20
2032	0.00	0.00	0.74	1.59	0.98	1.74	15.99	42.14
2033	0.00	0.00	1.35	0.93	1.19	1.56	14.38	41.85
2034	0.00	0.00	0.61	0.96	1.19	1.32	15.48	41.87
2035	0.00	0.00	0.06	0.39	2.13	2.25	20.84	45.28
Last 5 year average (%)	0.00	0.00	0.71	1.15	1.31	1.62	16.33	42.87
Last 10 year average (%)	0.00	0.05	0.91	1.27	1.54	1.45	14.45	38.93
Last 15 year average (%)	0.00	0.57	1.24	1.28	1.57	1.74	13.85	35.16
Last 20-year average (%)	0.00	1.57	2.03	2.15	2.57	3.81	13.84	31.34

Source: Research data (2016)

It would be observed that, the no budget constraint has zero unserved energy from year 2016 to year 2035. Similarly, the 3% of GDP has zero unserved energy from year 2027 to year 2035. However, the rest of the budget allocations expansion decisions witnessed some level of unserved energy throughout the planning horizon. Generally, as the budget allocation increases the level of unserved energy decreases.

Table 5.9 presents a cost-benefit analysis of the expansion plans for analysing the worthiness in a planned increase in the budget allocation. The present value of total expected cost (consisting of capital investment cost, fixed O&M cost, variable O&M cost, cost of unserved energy and electricity import cost), cost of unserved energy, budget left, increase in budget, committed budget and gains are summarized.

Table 5.9: Investment cost-benefit (in present value) for no budget and budget constraint, million$

Expansion plan	Total expected cost	Cost of unserved energy	Budget left	Increase in budget	Committed budget	Gains in reduced unserved energy	Gain from increased budget
No budget constr	28637.26	0.00	-	-	-	-	-
3% of GDP	29569.22	1210.89	1180.74	6779.46	5598.73	263.34	-5335.39
1.5% of GDP	31799.23	1474.23	218.48	1129.91	911.44	51.98	-859.45
1.25% of GDP	32269.81	1526.21	144.51	1129.91	985.40	286.53	-698.87
1% of GDP	32878.11	1812.74	87.54	1129.91	1042.37	960.96	-81.40
0.75% of GDP	33553.87	2773.71	40.17	1129.91	1089.74	5629.15	4539.41
0.5% of GDP	35199.49	8402.85	2.12	1129.91	1127.79	9732.91	8605.12
0.25% of GDP	37869.39	18135.76	0.00	-	-	-	-

Source: Research data (2016)

It can be seen that, as the budget allocation increases, the present value of the total expected cost decreases. The reverse would, of course, hold true in conformance with the observation that under budget constraint the central planner will resort to plants with lower capital cost but higher running cost that leads to increase in the total expected cost as the budget allocation decrease.

Further, the importance of increasing the budget allocation is revealed. For instance, to move from 0.25% of GDP to 0.5% of GDP as budget, $1,127.79 million was committed and this caused the cost of unserved energy to reduce from $18, 135.76 million to $8,402.85 million (i.e. a gain of $9732.91 million). This shows that it is worth increasing the budget allocation from 0.25% of GDP to 0.5% of GDP. A similarly observation can be made for an increase in the budget allocation from 0.5% of GDP to 0.75% of GDP. In the next chapter, we further discuss the above findings.

CHAPTER SIX

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The very purpose of this research has been to propose a multi-period stochastic MILP model to determine the *technology type*, *timing* and *number of units* of new generators to add to the electricity generation system under budget constraint in the context of a developing country. The aim of this last chapter is to shed light on the results obtained, and to show how this work enhances practice and policy. It begins with a further discussion of the findings presented in Chapter 5, makes conclusions on the research, makes recommendations based on the conclusions, presents the limitations of the study and the main contributions from the thesis and finally gives directions from which this work could be progressed.

6.2 Discussion of findings

Analysing the results from the two cases: no budget constraint and with budget constraint, the following were observed:

6.2.1 Alternative Generation Expansion Plans

1 If the **no budget constraint** is to be followed, the total new capacity that will be added to the generation system is 9,740 MW which consists of 240 MW of hydro, 300 MW of CCGT1, 450 MW of CCGT2 and 8,750 MW of coal2 in the 20-year horizon. With sufficient funds available, the yearly unserved energy will be zero and of course no cost to the economy as well.

2 If there is budget constraint and **0.25% of GDP** is set aside in each year as budget, the total new capacity that will be added to the system is 2,550 MW in the 20-year period. In this case, CCGT1 and CCGT2 are the generators suggested for construction which contribute 300 MW and 2,250 MW respectively to the total new capacity. With 0.25% of GDP, the yearly average unserved energy will be 31.34% which is on the high side compared to the average unserved energy of the no budget expansion plan. Also, the present value of the cost of unserved energy will be $18,135.76 million. The Ghanaian economy should expect a loss of about $18,135.76 million in the next 20 years if the 0.25% of GDP expansion plan is implemented.

3 Supposing **0.5% of GDP** is set aside in each year as budget, the total new generation capacity will be 4,950 MW with again only CCGT1 and CCGT2 doing the contribution of 900 MW and 4,050 MW respectively in the 20-year horizon. On setting aside 0.5% of GDP as budget in each year, the average unserved energy per year reduces tremendously to 13.84% compared to the average unserved energy of the 0.25% of GDP expansion plan. The present value of the cost of unserved energy whittles down to $8,402.85 million. Obviously, an increase in the budget allocation from 0.25% of GDP to 0.5% of GDP has led to a considerable cost saving to the economy of about a little over half ($9,732.91 million) of the cost of unserved energy of the 0.25% of GDP expansion plan. It is not surprising hereafter that, as the budget allocation increases, the average unserved energy and cost of unserved energy will decrease.

4 Further, in setting aside **0.75% of GDP** in each year as budget, the total new generation capacity will be 7,260 MW which consists of 60 MW of hydro and 7,200 MW of

CCGT2 in the 20-year period. The average unserved energy per year reduces tremendously again to 3.81% compared to the one for 0.5% of GDP expansion plan. The present value of the cost of unserved energy also reduces considerably to $2,773.71 million. A huge cost saving to the economy compared to the cost of unserved energy of the 0.5% of GDP expansion plan.

5 If Ghana opts to set aside **1% of GDP** in each year as budget, the total new capacity to be added in the 20-year horizon will be 7,340 MW with 240 MW of hydro, 300 MW of CCGT1, 6,300 MW of CCGT2 and 500 MW of coal2 contributing to the total. The average unserved energy per year again reduces to 2.57%. The present value of the cost of unserved energy to the economy reduces to $1,812.74 million but not so much as before. This signifies that at this point and after, the unserved energy and cost of unserved energy will be reducing at a slower pace as the budget allocation increase.

6 If the central planner decides to allocate **1.25% of GDP** as budget each year, the plan will be to add 7,840 MW to the current generation capacity. This will consist of 240 MW of hydro, 5,850 MW of CCGT2 and 1,750 MW of coal2 in the 20-year horizon. The average unserved energy per year is minimal, from 2.57% to 2.15%. The present value of the cost of unserved energy to the economy is also minimal, from $1,812.74 million to $1,526.21 million.

7 For **1.5% of GDP** as budget each year, the plan will be to add 240 MW of hydro, 4,950 MW of CCGT2 and 3,000 MW of coal2 given a total of 8,190 MW of new additional capacity in the 20-year period. The average unserved energy per year reduces to 2.03%

compared to the one for the 1.25% of GDP expansion plan. The present value of the cost of unserved energy to the economy reduces to $1,474.23 million.

8 Finally, for a **3% of GDP** as budget each year, the resulting plan will add a total new capacity of 9,190 MW to the generation system for the 20-year horizon. This total capacity is made up of 240 MW of hydro, 450 MW of CCGT2 and 9,000 MW of coal2. Clearly, 3% of GDP as budget is close to the no budget constraint. The average unserved energy per year has improved to 1.57% compared to the previous plan. The present value of the cost of unserved energy to the economy in this case will be $1,210.89 million.

6.3 Conclusions

The following conclusions are drawn based on the objectives of this study:

1 *Optimization Model for GEP:* In this thesis, stochastic optimization method has been applied to GEP of the Ghanaian electric power system. The stochastic optimization technique has been identified in the literature to offer a better approach to solving uncertainty problems in expansion planning. It provides a more realistic approach to planning for the future by including uncertainty explicitly into mathematical model. In addition to this, decisions made based on results from a stochastic optimization are better informed since more scenarios have been considered.

2 *Uncertain Electricity Demand:* One major uncertainty, the electricity demand, was assumed in this study and meaningful electricity demand scenarios generated based on Monte Carlo sampling approach of Breeden and Ingram (2010). Electricity demand was

estimated to follow a triangular distribution with a minimum increase of 1%, the most likely increase of 7% and a maximum increase of 15% per year. It was established that the scenarios based on the assumed distribution were quite comparable to the national demand forecast. However, the scenarios were found to be more reflective of the uncertainty in future electricity demand as the actual electric power demand upon realization could be up or below the national average forecast.

3 *Budget Constraint:* In this thesis, we have applied not only stochastic optimization method but also considered budget constraint, a reality in developing countries. In the case of the budget constraint, the available budget set aside in each year for generation expansion was varied over a range of 0.25% to 3% of projected national GDP. The budget constraint was important to help plan against reality and to help the central planner foresee the consequence (that is level of unserved energy) of his actions. The results indicated that, as the budget allocation increases, the level of unserved energy decreases considerably. In addition, the study provided a cost-benefit analysis procedure that showed the worthiness in a planned increase in the budget allocation from say 0.5% of GDP to 0.75% of GDP.

4 *Optimal Expansion Decisions:* On the substantive problem that constitutes the subject for this study, determining the *technology type, timing* and *number of units* of new generators to build in each year have been optimized for the case with no budget constraint and for various budget allocations in order to draw analogy. Further, the new capacities that should come on board taking into account construction time of the generators have been found. It was revealed that, under tight budget constraint the decision maker resorts to construction of generators with lower capital cost but higher

running cost. This reflects the trade-off between waiting for sufficient funds to accumulate to finance least cost generators and the incurring of high cost to the economy as a result of high levels of unserved demand and this is the dilemma developing countries are faced with.

6.4 Recommendations

On the basis of the findings, the following recommendations are made for researchers and stakeholders to consider.

1 The study employed stochastic optimization method which has been identified in the literature to offer a better approach to solving GEP problem. Given the many uncertain parameters with regards to generation capacity planning, researchers and planners of the Ghanaian electric power system, going forward, should adopt this method so that solutions that are robust to future uncertainties are obtained.

2 The study recognized the reality in developing countries and considered budget constraint in the optimization model. The budget constraint has been designed in such a way that the amount of unused budget allocation from the immediate past year is saved and invested for use as at when the expansion plan dictates. Government and stakeholders in developing countries should adopt this practice that can eliminate the over dependence on loans to finance needed generation capacity. This study recommends that, maybe, Ghana can allocate 0.75% of GDP solely for financing new generation capacity and electricity import to meet on average 96.19% of its yearly electricity demand from 2016 to 2035. The periodic budget constraint also offers valuable practical advice to international funding institutions such as the World Bank.

The World Bank for instance, could set as a condition to developing countries, to save a portion of their annual GDP towards future generation capacity according to what is suggested in the proposed model.

3 The results from the case study revealed that, under tight budget constraint the central planner will resort to construction of generators with lower capital cost but higher running cost which of course is the dilemma developing countries face. Even under budget constraint, a comprehensive plan that is optimal under a certain budget allocation of national GDP (such as derived using the proposed model) should be implemented. This is better than developing plans that assume sufficient funds availability which are never implemented or resorting to kneejerk actions that might be seriously sub-optimal.

4 Much as the proposed stochastic GEP model and its optimal results obtained in this thesis is recommended to Ghana, other developing countries, especially in Sub-Saharan Africa could adapt the model. Most Sub-Saharan African countries have similar electric power systems and are also faced with budget constraint for needed generation capacity just like Ghana.

6.5 Limitations of the Study

This study did not embark on the GEP in the context of a deregulated electricity market even though some of the existing and proposed plants are owned by IPPs. Also, the study considered electricity demand as the only uncertain parameter in the proposed stochastic MILP model, and so did not consider other equally important uncertain parameters such as fuel price (e.g. natural gas price) and hydro water inflows that could have made the expansion plan more robust. Furthermore, there is an increasing concern on carbon emissions and global warming issues, but this study did not consider carbon emissions constraint and cost.

Finally, time constraint partly limited the scope of the study. But for time, uncertainty in fuel price and hydro water inflows would have been considered to widen the scope of this study to better represent the GEP problem in Ghana.

6.6 Thesis Contributions

This thesis presents a new modelling approach which is specifically geared towards a developing country in the context of regulated electricity market. The main contributions of the thesis are as follow:

1 A contribution of the study is the novel development of a planning framework that considered the realities in developing countries, such as budget constraint. Such a model is important from the view point of determining the optimal expansion plan under tight budget constraint instead of resorting to kneejerk actions that might be seriously sub-optimal.

2 The study suggested that the amount of unused budget from the immediate past year is carried over to the next year. The idea is to encourage developing countries to develop the habit of saving unused budget allocation for future capacity expansion. This is a significant contribution of the thesis since no work has been reported that addresses the GEP problem in developing countries from this angle.

3. The analytical study reported in the thesis provide a new insight into the electric power system planning in developing countries, which have not been reported in previous studies. It would be observed from the results that as budget allocation increases, the level of unserved energy decreases. This helps the central planner quantify the consequences of his action which is the level of unserved energy to be incurred.

6.7 Scope for Future Research

This study has proposed a multi-period stochastic MILP model whose results can be improved with more accurate data. Further, there are more intriguing opportunities where this research can be extended to which are presented next:

1. Besides the electricity demand, more uncertainties such as fuel price (e.g. natural gas price) and hydro water inflows could be considered in the future research work.

2. In the process of scenario generation, the data set plays an essential role. The quality of the data gathered could affect the performance of the model. If the data are more reliable and complete, the scenarios are more useful. The performance of different scenario generation methods could be tested in the model.

3. More constraints than used in this study could be considered. For instance, the loss of load probability, generally assumed to be 0.1 days per year or less in practice, could be considered as a constraint to ensure the reliability of electric power system.

4. Currently, there is an increasing concern on carbon emission and global warming issues. This could also be focused on in the future research.

5 Future work could investigate where to locate the new generation units which involves a detailed feasibility study considering load centres, availability of fuel, water, transmission corridors and so forth.

6 In some GEP problems, capacity expansion in the transmission system needs to be considered as well. Future work could look at both generation and transmission expansion together.

7 Future work could model the GEP problem in a deregulated electricity market structure. This may involve huge modifications to the model as a deregulated system is quite different from a regulated authority.

REFERENCES

Adom, P. K. (2011). Electricity Consumption-Economic Growth Nexus : The Ghanaian Case. *Journal Of Energy*, *1*(1), 18–31.

Adom, P. K., Bekoe, W., & Akoena, S. K. K. (2012). Modelling aggregate domestic electricity demand in Ghana: An autoregressive distributed lag bounds cointegration approach. *Energy Policy*, *42*, 530–537.

Afful-Dadzie, A., Afful-Dadzie, E., Awudu, I., & Banuro, J. K. (2017). Power generation capacity planning under budget constraint in developing countries. *Applied Energy, 188,* 71-82.

Ahmed, S., & King, A. J. (2000). A Multi-stage Stochastic Integer Programming Approach for Capacity Expansion under Uncertainty.

Ahmed, S., King, A. J., & Parija, G. (2003). A multi-stage stochastic integer programming approach for capacity expansion under uncertainty. *Journal of Global Optimization*, *26*(1), 3–24.

Ahmed, S., & Sahinidis, N. V. (2003). An Approximation Scheme for Stochastic Integer Programs Arising in Capacity Expansion. *Operations Research*, *51*(March 2015), 461–471.

Al-shaalan, A. M. (2011). Essential aspects of power system planning in developing countries. *Journal of King Saud University - Engineering Sciences*, *23*(1), 27–32.

Benders, J. F. (1962). Partitioning Procedures for Solving Mixed Variables Programming. *Numerische Mathematik*, *2*, 238–252.

Berman, O., Ganz, Z., & Wagner, J. M. (1994). A stochastic optimization model for planning capacity expansion in a service industry under uncertian demand. *Naval Research Logistics*, *41*, 545–564.

Billinton, R., & Allan, R. N. (1994). *Reliability Evaluation of Power Systems* (Second Edi).

New York and Londan: Plenum Press.

Birge, J. R., & Louveaux, F. (1997). *Introduction to Stochastic Programming*. *October* (Vol. 49).

Breeden, J. L., & Ingram, D. (2010). Monte Carlo Scenario Generation for Retail Loan Portfolio, *61*(3), 399–410.

Buehring, W., Huber, C., & Marques de Souza, J. (1984). *Expansion Planning for Electrical Generating Systems—A Guidebook*. Vienna, Austria.

Bukari, D. (2012). Ghana's Electricity Industry: Can Liberalization be Effective in the Absence of Overcapacity? *CEPMLP Annual Review*, *16*(2013).

Chao, X., Chen, H., & Zheng, S. (2008). Dynamic Capacity Expansion for a Service Firm with Capacity Deterioration and Supply Uncertainty. *Operations Research*, *57*(1), 82–93.

Chuang, A. S., Wu, F., & Varaiya, P. (2001). A game-theoretic model for generation expansion planning: problem formulation and numerical comparisons. *IEEE Transactions on Power Systems*, *16*(4), 885–891.

Dantzig, G. B. (1955). Linear Programming Under Uncertainty. *Management Science*, *1*(12 Supplement), 197–206.

Deloitte Conseil. (2015). *European energy market reform Country profile : Spain Contents*.

Eberhard, A., Foster, V., Briceño-Garmendia, C., Ouedraogo, F., Camos, D., & Shkaratan, M. (2008). *Africa Infrastructure Underpowered : The State of the Power Sector in Sub-Saharan Africa*.

Eberhard, A., Rosnes, O., Shkaratan, M., & Vennemo, H. (2011). *Africa's Power Infrastructure: Investment, Integration, Efficiency*.

Energy Commission. (2014). *National Energy Statistics 2000-2013*. Retrieved from http://www.energycom.gov.gh/

Energy Commission. (2015a). *2015 Energy (Supply and Demand) Outlook for Ghana*.

Energy Commission. (2015b). *Electricity Wholesale Supply Licence Register*. Retrieved from http://www.energycom.gov.gh/index.php/20-regulation/96-electricity-wholesale-supply-licence-register

Energy Commission. (2015c). *National Energy Statistics 2005-2014*. Retrieved from http://www.energycom.gov.gh/

Energy Commission. (2016). Mandate and Functions. Retrieved February 4, 2016, from http://www.energycom.gov.gh/

Faleye, O. O. (2012). *Modelling Demand Uncertainties in Generation-Transmission Expansion planning A case study of the Nigerian Power System*. Royal Institute of Technology.

Feng, Y., & Ryan, S. M. (2013). Scenario construction and reduction applied to stochastic power generation expansion planning. *Computers & Operations Research*, *40*(1), 9–23.

Firmo, T. H., & Legey, L. L. F. (2002). Generation expansion planning: an iterative genetic algorithm approach. *IEEE Transactions on Power Systems*, *17*(3), 901–906.

Fleten, S. E., & Pettersen, E. (2005). Constructing bidding curves for a price-taking retailer in the Norwegian electricity market. *IEEE Transactions on Power Systems*, *20*(2), 701–708.

Freund, R. (2004). Benders' Decomposition Methods for Structured Optimization, including Stochastic Optimization. *Massachusetts Institute of Technology*. Retrieved from http://mit-ocw.udem.edu.co/courses/sloan-school-of-management/15-094j-systems-optimization-models-and-computation-sma-5223-spring-2004/lecture-notes/benders_art.pdf

Fukuyama, Y., & Hsaio-Dong Chiang. (1996). A parallel genetic algorithm for generation expansion planning. *IEEE Transactions on Power Systems*, *11*(2), 955–961.

Gandulfo, W., & Gil, E. (2014). Generation Capacity Expansion Planning under Demand Uncertainty Using Stochastic Mixed-Integer Programming, (c).

García-bertrand, R., Kirschen, D., & Conejo, A. J. (2008). Optimal Investments in Generation Capacity Under Uncertainty, 14–20.

Gentle, J. E. (2003). Random Number Generation and Monte Carlo Methods. *Statistics and Computing*, 229–281.

Geoffrion, A. M. (1972). Generalized Benders decomposition. *Journal of Optimization Theory and Applications*, *10*(4), 237–260.

Gröwe-Kuska, N., Heitsch, H., & Römisch, W. (2003). Scenario reduction and scenario tree construction for power management problems. *2003 IEEE Bologna PowerTech - Conference Proceedings*, *3*, 152–158.

Gu, Y. (2011). Long-term power system capacity expansion planning considering reliability and economic criteria.

Hobbs, B. F. (1995). Optimization methods for electric utility resource planning. *European Journal of Operations Research*, *83*, 1–20.

Høyland, K., Kaut, M., & Wallace, S. W. (2003). A heuristic for moment-matching scenario generation. *Computational Optimization and Applications*, *24*(2–3), 169–185.

Høyland, K., & Wallace, S. W. (2001). Generating Scenario Trees for Multistage Decision Problems. *Management Science*, *47*(2), 295–307.

Huang, K., & Ahmed, S. (2009). The Value of Multistage Stochastic Programming in Capacity Planning Under Uncertainty, (2003), 1–12.

Inoue, M., Kimura, G., & Ueda, T. (1994). Efficient method for capacity expansion planning of telecommunication network facilities. *Transactions of the Institute of Electronics, Information and Communication Engineers B-I*, *J77B–I*(1), 1–7.

International Energy Agency. (2014). *Africa Energy Outlook*. Retrieved from www.iea.org

ISSER. (2005). *Guide to Electric Power in Ghana*.

ISSER. (2014). *State of the Ghanaian economy*.

Iwayemi, A. (2008). Nigeria's dual energy problems: policy issues and challenges. *International Association for Energy Economics*, *53*, 17-21.

Jin, S. (2009). *Long Term Power Generation Planning Under Uncertainty*. Iowa State University.

Jin, S. (2012). *Electricity System Expansion Studies to Consider Uncertainties and Interactions in Restructured Markets*. Iowa State University.

Jordan, R. L. (2013). *Incorporating endogenous demand dynamics into long-term capacity expansion power system models for Developing countries* (Doctoral dissertation, Massachusetts Institute of Technology).

Kagiannas, A. G., Askounis, D. T., & Psarras, J. (2004). Power Generation Planning: A Survey from Monopoly to Competition. *International Journal of Electrical Power and Energy Systems*, *26*, 413–421.

Kall, P., & Mayer, J. (2005). *Stochastic Linear Programming Models, Theory, and Computation*. New York: Kluwer Academic.

Kapika, J., & Eberhard, A. (2015). *Power-sector reform and regulation in Africa: lessons from Kenya, Tanzania, Uganda, Zambia, Namibia and Ghana*. HSRC Press.

Kaut, M., & Wallace, S. W. (2003). Evaluation of scenario-generation methods for stochastic programming, (1), 1–14.

Khan, A. Z., Yingyun, S., Ashfaq, A., & Malik, S. M. (2014). the Equilibrium Between System Reliability and Cost : A Pakistani Case Study, 71–76.

Kothari, R. P., & Kroese, D. P. (2009). Optimal Generation Expansion Planning Via the Cross-Entropy Method, 1482–1491.

Kristoffersen, T. K. (2007). Stochastic programming with applications to power systems, (April).

Lee, C. Y. (2000). Cell planning with capacity expansion in mobile communications: a tabu search approach. *IEEE Transactions on Vehicular Technology*, *49*(5), 1678–1691.

Li, S., Coit, D. W., Selcuklu, S., & Felder, F. A. (2014). Electric Power Generation Expansion Planning : Robust Optimization Considering Climate Change.

Li, Y. F., Huang, G. H., Li, Y. P., Xu, Y., & Chen, W. T. (2010). Regional-scale electric power system planning under uncertainty — A multistage interval-stochastic integer linear programming approach. *Energy Policy*, *38*(1), 475–490.

Malcolm S.A. and Zenios S.A. (1994). Robust Optimization For Power Systems Capacity Expansion under Uncertainty. *The Journal of the Operational Research Society*, *45*(9), 1040–1049.

Malik, A. S., & Kuba, C. (2013). Power Generation Expansion Planning Including Large Scale Wind Integration : A Case Study of Oman, *2013*.

Millennium Challenge Corporation. (2012). *Increasing Private Sector Investment through Power Sector Reform*.

MirHassani, S. A., & Noori, R. (2011). Implications of capacity expansion under uncertainty in oil industry. *Journal of Petroleum Science and Engineering*, *77*(2), 194–199.

MoEn. (2016). Mandate and Functions. Retrieved February 4, 2016, from http://www.energy.go.ke/index.php/about-us/background.html

Mulvey, J. M., Vanderbei, R. J., & Zenios, S. A. (1995). Robust Optimization of Large-Scale Systems. *Operations Research*, *43*(2), 264–281. http://doi.org/10.1287/opre.43.2.264

Musmanno, R., Scordino, N., Triki, C., & Violi, a. (2009). A multistage formulation for generation companies in a multi-auction electricity market. *IMA Journal of Management Mathematics*, *21*(2), 165–181.

NDPC. (2010). *Policy Framework Final Draft* (Vol. I).

Nowak, M. P., & Römisch, W. (2000). Stochastic Lagrangian Relaxation Applied to Power Scheduling in a Hydro-Thermal System under Uncertainty. *Annals of Operations Research*, *100*(1–4), 251–272.

Peng, C., Erhun, F., Hertzler, E. F., & Kempf, K. G. (2012). Capacity Planning in the Semiconductor Industry: Dual-Mode Procurement with Options. *Manufacturing & Service Operations Management*, *14*(2), 170–185.

PSEC, & GRIDCo. (2010). *Ghana wholesale power reliability assessment. Final report*.

PURC. (2016). Mandate and Function. Retrieved February 4, 2016, from http://www.purc.com.gh/

Raeside, D. E. (1976). Monte Carlo principles and applications. *Physics in Medicine and Biology*, *21*(2), 181–197.

Ravadanegh, S. N., & Roshanagh, R. G. (2014). On optimal multistage electric power distribution networks expansion planning. *International Journal of Electrical Power & Energy Systems*, *54*, 487–497.

Rebennack, S. (2014). Generation expansion planning under uncertainty with emissions quotas. *Electric Power Systems Research*, *114*, 78–85.

Rosenthal, R. E. (2013). GAMS — A User ' s Guide, (November).

Russell, R. S., & Taylor, B. W. (2011). *Operations Management* (7th Editio). River Street, Hoboken: John Wiley & Sons, Inc.

Sahinidis, N. V. (2004). Optimization under uncertainty: State-of-the-art and opportunities. *Computers and Chemical Engineering*, *28*(6–7), 971–983.

Shapiro, A. (2003). Inference of statistical bounds for multistage stochastic programming problems. *Mathematical Methods of Operations Research*, *58*(1), 57–68.

Shapiro, A., & Philpott, A. (2007). A tutorial on stochastic programming. *Manuscript. Available at www2. Isye. Gatech. Edu …*, 1–35. Retrieved February 6, 2016 from http://stoprog.org/stoprog/SPTutorial/TutorialSP.pdf

Sharma, D. (2009). *Generation Capacity Expansion Planning in Deregulated Electricity Markets*. University of Waterloo.

Shiina, T. (2011). Stochastic Programming Model for Power Generation, *5*(6), 753–758.

Shiina, T., & Birge, J. R. (2003). Multistage Stochastic Programming Model for Electric Power Capacity Expansion Problem, *20*, 379–397.

Taghavi, M., & Huang, K. (2014). Stochastic capacity expansion with multiple sources of capacity. *Operations Research Letters*, *42*(4), 263–267.

Tekiner, H. (2010). *Multi-objective Stochastic Model for Electricity Generation Expansion Planning Problems Considering Risk*. Rutgers, The State University of New Jersey.

Tekiner-Mogulkoc, H., Coit, D. W., & Felder, F. A. (2012). Electric power system generation expansion plans considering the impact of Smart Grid technologies. *International Journal of Electrical Power & Energy Systems*, *42*(1), 229–239.

Tidball, R., Bluestein, J., Rodriguez, N., & Knoke, S. (2010). Cost and performance assumptions for modeling electricity generation technologies. *Contract*, *303*, 275-3000.

Tractebel Engineering. (2011). *Generation Master Plan Study for Ghana*.

Uchchkotiya, A. K., Singh, R., & Trivedi, A. S. (2013). Evolutionary Techniques of GAMS used in Optimization of economic load dispatch in Power system. *International Journal of Engineering Research & Technology*, *2*(9), 2359–2367.

Vithayasrichareon, P., & MacGill, I. F. (2012). A Monte Carlo based decision-support tool for assessing generation portfolios in future carbon constrained electricity industries. *Energy Policy*, *41*, 374–392.

Vithayasrichareon, P., MacGill, I., & Wen, F. (2009). Monte-Carlo optimization framework for assessing electricity generation portfolios. *2009 Australasian Universities Power Engineering Conference*, 2–7.

Volling, T., Matzke, A., Grunewald, M., & Spengler, T. S. (2013). Planning of capacities and orders in build-to-order automobile production: A review. *European Journal of Operational Research*, *224*(2), 240–260.

Voropai, N. I., & Ivanova, E. Y. (2002). Multi-criteria decision analysis techniques in electric power system expansion planning. *International Journal of Electrical Power & Energy Systems*, *24*(1), 71–78.

VRA. (2015). Power Generation: Facts & Figures. Retrieved December 31, 2015, from http://www.vra.com/resources/facts.php

Wallace, S. W. (2003). Stochastic Programming Models in Energy, *10*, 637–677.

World Bank. (2014). Working for a World Free of Poverty. Retrieved May 1, 2016, from http://www.worldbank.org/en/country/ghana

World Bank, IFC, & MIGA. (2013). Evaluation of the World Bank Group's Support for Electricity Access, 1–34.

Zhu, J., & Chow, M. (1997). A Review of Emerging Techniques on Generation Expansion Planning. *IEEE Transactions on Power Systems*, *12*(4).

Zhu, Y., Li, Y. P., & Huang, G. H. (2013). Planning carbon emission trading for Beijing's electric power systems under dual uncertainties. *Renewable and Sustainable Energy Reviews*, *23*, 113–128.

APPENDICES

APPENDIX A. Electricity demand scenarios in GWh

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
scen-1	19280.28	20723.21	22342.57	23627.82	25010.76	27379.89	27939.99	30547.83	33569.41	36541.77	37594.47	40106.84	44303.72	48571.72	51679.22	57952.71	64083.93	66066.94	73900.82	78577.67
scen-2	18748.58	20274.79	21965.48	23181.51	24495.40	26960.74	29658.12	31996.84	36116.44	40144.71	42234.89	45923.13	51732.88	54506.78	58587.77	60861.22	69241.32	75176.38	76760.16	82733.96
scen-3	18745.14	19955.83	21122.28	23622.45	26609.56	28364.53	29969.67	31329.56	32759.36	35487.87	37849.80	40375.95	43964.21	46621.50	50454.90	52989.58	55537.89	59893.47	61995.21	66320.47
scen-4	19717.49	21336.51	23081.62	24646.77	25574.58	27538.65	29942.02	33294.90	36665.32	37519.09	40353.19	44888.05	47937.35	52053.46	55838.37	59941.34	64142.86	68152.30	72663.53	76723.13
scen-5	18839.50	20193.45	21099.03	22593.79	23831.84	25783.10	27728.35	28973.80	32344.96	35059.61	37617.50	40069.69	41630.01	45612.52	48799.76	53321.36	57553.68	63365.75	64765.88	68037.06
scen-6	19047.11	20649.66	22210.44	24439.69	25301.78	26533.75	28814.20	30817.41	32751.85	34199.59	37213.76	41476.34	44571.14	46195.42	50493.73	53825.58	57594.55	61742.50	64844.63	68781.62
scen-7	18936.64	19999.76	22118.61	24161.67	25518.12	27700.02	29216.34	30282.15	31055.48	32924.14	36094.68	38193.66	40211.78	43076.55	45426.95	48222.68	49607.70	53148.26	55810.27	61664.20
scen-8	18338.65	19848.25	21169.22	23731.17	24678.06	27481.63	29713.46	31558.05	32950.36	35296.73	37109.88	42024.98	43785.61	44880.70	47659.01	51273.58	57094.23	61386.43	65456.57	72180.03
scen-9	18996.59	20264.71	22034.66	23078.56	24634.85	26495.39	29116.64	31311.01	33432.25	35878.18	37749.26	40811.95	43744.85	47511.55	52636.92	55992.99	59272.75	62698.42	65472.24	70355.74
scen-10	18577.35	20182.08	22039.98	23819.22	26093.34	27281.09	29959.45	31450.07	35229.24	36379.95	37540.69	41167.84	43819.64	46892.84	48793.69	50745.98	53121.71	54682.08	59551.91	64007.09
scen-11	18882.47	20965.29	22892.50	23723.09	25676.30	27958.87	28547.68	30488.66	32500.77	34331.83	38742.20	42524.04	46241.16	49342.67	53825.23	56866.16	60433.87	64552.20	72144.98	75087.85
scen-12	18923.51	21208.49	22808.54	24454.59	27494.67	28902.86	30763.35	32780.38	34644.23	37165.43	38759.66	41617.04	46704.58	50279.51	55873.38	60575.26	64734.20	70375.40	72657.56	79406.56
scen-13	19412.78	19991.29	21466.10	23461.99	25747.42	27301.65	30693.79	33695.53	36579.95	40626.34	44948.11	47959.97	49925.59	55895.46	61320.19	66681.30	71080.19	72592.41	75944.28	79421.88
scen-14	19540.85	20955.79	21967.34	24368.98	25926.78	27488.52	30081.61	31622.87	33806.34	35594.93	39394.08	42563.71	45289.59	48238.81	53274.07	57462.28	64072.97	68796.18	72976.08	80667.85
scen-15	19339.49	21311.12	22517.65	24499.43	26121.19	28696.50	31322.96	33466.31	34626.34	36932.26	39201.76	42678.09	45211.22	49606.11	51808.86	55909.08	62620.63	65973.93	73668.32	76604.96
scen-16	18668.94	20616.63	21321.28	22781.90	24906.64	26246.01	27934.75	29769.06	31982.78	33771.32	36414.40	38251.26	39581.55	43902.06	45635.39	49457.63	54892.25	57774.22	64629.08	71259.22
scen-17	18586.08	19709.39	21025.45	21961.28	23744.14	24642.76	25874.71	28128.47	30177.57	31619.72	35766.80	38293.49	38890.84	41521.17	43906.77	47970.18	53177.15	58481.33	61238.40	63634.63
scen-18	19592.99	21126.90	23036.30	24041.38	25359.85	25989.87	28599.92	31334.10	34354.88	36448.50	38974.64	41951.23	46049.67	49595.97	52068.28	54684.17	58147.56	62665.78	66539.35	71495.08
scen-19	19870.87	22162.33	25082.85	27636.12	29474.03	32359.69	36572.65	38580.42	40389.51	43914.83	44859.50	47615.16	51762.71	53799.21	55911.20	59132.12	63021.75	67852.53	71872.69	76042.45
scen-20	18895.59	20594.96	22330.61	23811.14	26638.48	28855.02	30979.91	32582.70	35136.56	38374.86	41048.43	45584.31	48181.90	52277.19	57942.97	61236.94	65130.40	66467.66	70318.86	79316.22

APPENDIX B: Electricity generation (GWh) from all generators for electricity demand scenarios in the case of 0.75% of GDP budget allocation

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
scen-1	18095.97	18095.97	18095.97	21446.67	24797.37	27379.89	27939.99	30547.83	33569.41	36541.77	37594.47	40106.84	44303.72	48571.72	51181.06	57952.71	61970.43	65275.34	68671.83	72022.53
scen-2	18095.97	18095.97	18095.97	21446.67	24495.40	26960.74	28148.07	31498.77	35164.83	38515.53	38515.53	45216.93	48567.63	51918.33	55269.03	58619.73	61970.43	65321.13	68671.83	72022.53
scen-3	18095.97	18095.97	18095.97	21446.67	24797.37	28148.07	28148.07	31329.56	32759.36	35487.87	37849.80	40375.95	43964.21	45949.73	50454.90	52989.58	55174.89	57497.73	59515.40	63667.65
scen-4	18095.97	18095.97	18095.97	21446.67	24797.37	27538.65	28148.07	31498.77	35164.83	37519.09	38515.53	44888.05	47937.35	51918.33	55269.03	58619.73	61970.43	65321.13	68671.83	72022.53
scen-5	18095.97	18095.97	18095.97	21446.67	23831.84	25783.10	27728.35	28973.80	32344.96	35059.61	37617.50	40069.69	41630.01	44940.75	48799.76	53321.36	57315.32	60831.12	62175.25	65315.58
scen-6	18095.97	18095.97	18095.97	21446.67	24797.37	26533.75	28148.07	30817.41	32751.85	34199.59	37213.76	41476.34	44571.14	46195.42	49318.29	53825.58	57594.55	59532.95	62250.84	66030.36
scen-7	18095.97	18095.97	18095.97	21446.67	24797.37	27700.02	28148.07	30282.15	31055.48	32924.14	36094.68	38193.66	40211.78	42404.78	45426.95	48222.68	49002.60	51022.33	53577.86	59197.63
scen-8	18095.97	18095.97	18095.97	21446.67	24678.06	27481.63	28148.07	31498.77	32950.36	35296.73	37109.88	42024.98	43785.61	44208.94	47659.01	51273.58	56784.82	58930.97	62838.30	69292.83
scen-9	18095.97	18095.97	18095.97	21446.67	24634.85	26495.39	28148.07	31311.01	33432.25	35878.18	37749.26	40811.95	43744.85	47511.55	51461.48	55992.99	59272.75	60488.87	62853.36	67541.51
scen-10	18095.97	18095.97	18095.97	21446.67	24797.37	27281.09	28148.07	31450.07	35164.83	36379.95	37540.69	41167.84	43819.64	46892.84	48793.69	48904.62	52455.90	53890.48	57169.83	61446.81
scen-11	18095.97	18095.97	18095.97	21446.67	24797.37	27958.87	28148.07	30488.66	32500.77	34331.83	38515.53	42524.04	46241.16	49342.67	52661.32	56866.16	60433.87	62342.66	68671.83	72022.53
scen-12	18095.97	18095.97	18095.97	21446.67	24797.37	28148.07	28148.07	31498.77	34644.23	37165.43	38515.53	41617.04	46704.58	50279.51	55269.03	58619.73	61970.43	65321.13	68671.83	72022.53
scen-13	18095.97	18095.97	18095.97	21446.67	24797.37	27301.65	28148.07	31498.77	35164.83	38515.53	38515.53	45216.93	48567.63	51918.33	55269.03	58619.73	61970.43	65321.13	68671.83	72022.53
scen-14	18095.97	18095.97	18095.97	21446.67	24797.37	27488.52	28148.07	31498.77	33806.34	35594.93	38515.53	42563.71	45289.59	48238.81	53274.07	57462.28	61970.43	65321.13	68671.83	72022.53
scen-15	18095.97	18095.97	18095.97	21446.67	24797.37	28148.07	28148.07	31498.77	34626.34	36932.26	38515.53	42678.09	45211.22	49606.11	50644.95	55909.08	61970.43	64488.98	68671.83	72022.53
scen-16	18095.97	18095.97	18095.97	21446.67	24797.37	26246.01	27934.75	29769.06	31982.78	33771.32	36414.40	38251.26	39581.55	43230.29	45635.39	49457.63	54393.62	55529.64	62043.92	68408.85
scen-17	18095.97	18095.97	18095.97	21446.67	23744.14	24642.76	25874.71	28128.47	30177.57	31619.72	35766.80	38187.55	38785.07	41521.17	43906.77	47970.18	52178.94	56142.08	58788.87	61089.25
scen-18	18095.97	18095.97	18095.97	21446.67	24797.37	25989.87	28148.07	31334.10	34354.88	36448.50	38515.53	41951.23	46049.67	49595.97	50904.36	54684.17	58147.56	60456.23	63877.78	68635.28
scen-19	18095.97	18095.97	18095.97	21446.67	24797.37	28148.07	28148.07	31498.77	35164.83	38515.53	38515.53	45216.93	48567.63	51918.33	55269.03	58619.73	61970.43	65321.13	68671.83	72022.53
scen-20	18095.97	18095.97	18095.97	21446.67	24797.37	28148.07	28148.07	31498.77	35136.56	38374.86	38515.53	45216.93	48181.90	51918.33	55269.03	58619.73	61970.43	65321.13	67506.11	72022.53

APPENDIX C: Electricity import (GWh) for electricity demand scenarios in the case of 0.75% of GDP budget allocation

	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
scen-1	0.00	0.00	6.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	498.16	0.00	2113.50	791.60	2956.03	3143.11
scen-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	341.36	313.29	0.00	0.00	0.00	2800.27	3070.41	3309.36
scen-3	0.00	0.00	6.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	671.77	0.00	0.00	362.99	2395.74	2479.81	2652.82
scen-4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	529.54	2172.43	791.60	2906.54	3068.93
scen-5	0.00	5.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	671.77	0.00	0.00	238.36	2534.63	2590.64	2721.48
scen-6	0.00	0.00	6.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1175.44	0.00	0.00	2209.55	2593.79	2751.26
scen-7	0.00	0.00	0.00	7.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	671.77	0.00	0.00	605.10	2125.93	2232.41	2466.57
scen-8	0.00	0.00	0.00	0.00	0.00	0.00	10.28	0.00	0.00	0.00	0.00	0.00	0.00	671.77	0.00	0.00	309.41	2455.46	2618.26	2887.20
scen-9	0.00	0.00	6.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1175.44	0.00	0.00	2209.55	2618.89	2814.23
scen-10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.78	0.00	0.00	0.00	0.00	0.00	0.00	1841.36	665.81	791.60	2382.08	2560.28
scen-11	0.00	0.00	6.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.47	0.00	0.00	0.00	1163.91	0.00	0.00	2209.55	2885.80	3003.51
scen-12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2589.37	984.61	2906.30	3176.26
scen-13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1881.46	0.00	1533.60	3037.77	3176.88
scen-14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1003.59	2751.85	2919.04	3226.71
scen-15	0.00	0.00	0.00	0.00	8.28	0.00	0.00	0.00	0.00	0.00	7.47	0.00	0.00	0.00	1163.91	0.00	650.20	1484.95	2946.73	3064.20
scen-16	0.00	0.00	6.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	671.77	0.00	0.00	498.63	2244.58	2585.16	2850.37
scen-17	0.00	5.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	105.94	105.77	0.00	0.00	0.00	998.21	2339.25	2449.54	2545.39
scen-18	0.00	0.00	0.00	7.43	0.00	0.00	0.00	0.00	0.00	0.00	7.47	0.00	0.00	0.00	1163.91	0.00	0.00	2209.55	2661.57	2859.80
scen-19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	693.71	0.00	0.00	241.26	2531.40	2874.91	3041.70
scen-20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1199.90	544.26	665.81	791.60	2812.75	3172.65

APPENDIX D: Unserved electricity demand (GWh) for electricity demand scenarios in the case of 0.75% of GDP budget allocation

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
scen-1	1184.31	2627.24	4239.93	2181.15	213.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2272.96	3412.04
scen-2	652.61	2178.82	3869.51	1734.84	0.00	0.00	1510.05	498.07	951.61	1629.18	3719.36	706.20	2823.90	2275.15	3318.74	2241.49	7270.89	7054.98	5017.92	7402.07
scen-3	649.17	1859.86	3019.65	2175.78	1812.19	216.46	1821.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-4	1621.52	3240.54	4985.65	3200.10	777.21	0.00	1793.95	1796.13	1500.49	0.00	1837.66	0.00	0.00	135.13	569.34	792.07	0.00	2039.57	1085.16	1631.67
scen-5	743.53	2091.50	3003.06	1147.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-6	951.14	2553.69	4107.80	2993.02	504.41	0.00	666.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-7	840.67	1903.79	4022.64	2707.58	720.75	0.00	1068.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-8	242.68	1752.28	3073.25	2284.50	0.00	0.00	1555.11	59.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-9	900.62	2168.74	3932.03	1631.89	0.00	0.00	968.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-10	481.38	2086.11	3944.01	2372.55	1295.97	0.00	1811.38	0.00	45.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-11	786.50	2869.32	4789.86	2276.42	878.93	0.00	399.61	0.00	0.00	0.00	219.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	587.35	61.81
scen-12	827.54	3112.52	4712.57	3007.92	2697.30	754.79	2615.28	1281.61	0.00	0.00	244.13	0.00	0.00	0.00	604.35	1955.53	174.40	4069.66	1079.43	4207.77
scen-13	1316.81	1895.32	3370.13	2015.32	950.05	0.00	2545.72	2196.76	1415.12	2110.81	6432.58	2743.04	1357.96	3977.13	6051.16	6180.11	9109.76	5737.67	4234.68	4222.47
scen-14	1444.88	2859.82	3871.37	2922.31	1129.41	0.00	1933.54	124.10	0.00	0.00	878.55	0.00	0.00	0.00	0.00	0.00	1098.94	723.20	1385.20	5418.60
scen-15	1243.52	3215.15	4421.68	3052.76	1315.54	548.43	3174.89	1967.54	0.00	0.00	678.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2049.76	1518.23
scen-16	572.97	2520.66	3218.64	1335.23	109.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-17	490.11	1607.44	2929.48	514.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-18	1497.02	3030.93	4940.33	2587.28	562.48	0.00	451.85	0.00	0.00	0.00	451.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
scen-19	1774.90	4066.36	6986.88	6189.45	4676.66	4211.62	8424.58	7081.65	5224.68	5399.30	6343.97	2398.23	3195.08	1187.17	642.17	512.39	810.05	0.00	325.95	978.23
scen-20	799.62	2498.99	4234.64	2364.47	1841.11	706.95	2831.84	1083.93	0.00	0.00	2532.90	367.38	0.00	358.86	1474.05	2072.95	2494.15	354.93	0.00	4121.05