UNIVERSITY FOR DEVELOPMENT STUDIES

AN OPTIMAL ENERGY MIX INVESTMENT FOR GHANA

OSMAN KASIMU

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AN OPTIMAL ENERGY MIX INVESTMENT FOR GHANA

BY

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THESIS SUBMITTED TO THE DEPARTMENT OF MATHEMATICS, FACULTY OF MATHEMATICAL SCIENCES, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN MATHEMATICS

NOVEMBER, 2015

DECLARATION

Student

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this University or elsewhere. Related works by others which served as a source of knowledge has been duly referenced and acknowledged.

Candidate's Signature ………………… Date ………………………

Name: Osman Kasimu

Supervisors'

I hereby declare that the preparation and presentation of this thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.

Supervisor's Signature ………………………. Date ……………………….

Name: Dr. Stephen B. Twum

ABSTRACT

This study aimed at finding a minimum cost of investment in Renewable Energy (RE) sources, specifically in Hydro, Wind, Solar and Biomass that will meet projected demand levels in specific time periods in the future and ensure a modest (10%), (20%) or an ambitious (30%) incorporation of these renewable energy sources. To do this, a relevant optimization model was formulated and discussed. The Levelized Cost of Energy (LCOE) model adopted for the purpose was also discussed in detail. Projected demand cases were assumed or envisaged and each discussed under three specific scenarios (C1, C2 and C3). Secondary data from Volta River Authority (VRA) and other relevant sources were presented and ran using risk optimizer 6.3 software to generate the required solutions. The results showed that for the projected demands of energy to be met with (10%) share from RE, greater output would be from Wind, followed by Hydro, Solar and Biomass together with the existing plants to meet incremental demand. For (20%) share, Wind and Solar would contribute more whiles for (30%) share, Solar and Hydro would contribute more. The study further revealed that the optimal costs of producing power to meet the projected demands under C1, C2 and C3 were $30,525M, $25,085M and $23,119M respectively. The results illustrated that there is a reduction in the cost of power production from scenario C1 to C3 in all the demand cases, an indication that when more of RE sources are incorporated into Ghana's current generation mix, the cost of producing power to meet incremental demand could be substantially reduced. Among the recommendations offered was that, since RE investment incur low generation cost due to little or no fuel cost, the government should placed emphasis on the development of RE generation to meet incremental demand for energy at minimum cost in the country.

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DEDICATION

I dedicate this thesis to my beloved friend Mr. Kwara Nantomah, Lecturer, Department of Mathematics, University for Development Studies.

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ACRONYMS AND ABBREVIATIONS

AEA	Alternative Energy Africa
CC	Combine cycle
CCGT	Combined Cycle Gas Turbine
CEB	Communauté Electrique du Benin
DFO	Distillate Fuel Oil
DG	Diesel Generator
ESI	Electricity Supply Industry
EC	Electricity Company
ECG	Electricity Company of Ghana
GDP	Gross Domestic Product
GEP	Guide to Electric Power
GoG	Government of Ghana's
GRIDCo	Ghana Grid Company
GWh	GigaWatts hours
GSS	Ghana Statistical Service
Hr	Hours
IBFS	Initial Basic Feasible Solution
IPPs	Independent Power Producers
IRENA	International Renewable Energy Agency
IMF	International Monetary Found
LPR	Linear Programming Relaxation
LCO	Light Crude Oil

MILP	Mixed Integer Linear Programming
MoE	Ministry of Energy
MW	Megawatts
MWh	Megawatts hours
m/s	Metres per Second
NED	Northern Electricity Department
NEDCo	Northern Electricity Distribution Company
NESRP	Northern Electrification & System Reinforcement Project
NES	National Electrification Scheme
NREL	National Renewable Energy Laboratory
RE	Renewable Energy
RETs	Renewable Energy Technologies
SAPP	Sunon-Asogli Power Plant
SNEP	Strategic National Energy Plan
TAPCO	Takoradi Thermal Power Station
TTPP	Tema Thermal 1 Power P
USD	United States Dollars
VALCO	Volta Aluminum Company
VRA	Volta River Authority
WAPP	West Africa Power Pool
WECS	Wind Electric Conversion Systems
Yr	Year

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The availability of adequate and affordable energy is what has prompted the development of industrialized countries over the past 200 years (Dilip *et al.*, 2009). Access to energy is fundamental to improving the quality of life and is the key for economic development. In the developing world, energy poverty is still wide spread. According to the International Energy Agency (IEA) 2012 world energy outlook report, nearly 1.6 billion people, one fourth of the world population, currently live without electricity. And yet the electricity required for people to read at night, pump a minimal amount of drinking water and listen to radio broadcasts would amount to less than one per cent of the overall global energy demand. The tenet is straight, without energy there can be no development (Dilip *et al.*, 2009).

Energy usage has been the essence of life since creation and it is part and parcel of our social and economic life. It has become a political commodity necessary for information, communication, technology, for hospitals, schools and other spheres of human endeavor. Energy is a very critical factor in the development process of any country and if the economy is to grow, the people will need to consume more energy (Akuffo, 2007).

Ghana has made tremendous strides in electricity penetration as compared to other African countries. According to Iddrisu (2014), the country enjoys a total installed capacity of 2,813.5MW mainly from hydro, thermal and more recently from solar. Over 70% of Ghanaians have access to electricity but affordability has been a major issue to both household and corporate consumers (Iddrisu, 2014).

Notwithstanding this feat, the country's electricity demand is increasing at the rate of 12%, which calls for urgent measures to address the shortfall.

For almost half a century now, the main source of electricity generation in Ghana has been through hydro. Hydroelectricity accounts for over 60% of the total generation, and comprise Hydro power from Akosombo, Kpong and Bui with generating capacities of 1,020 MW, 160 MW and 400 MW respectively. These sources of electricity provide enormous benefits to the country in terms of transportation, tourism, fishing and irrigated farming activities among others. They also afford the country an opportunity to earn some foreign exchange through the export of some electricity to Togo and Benin.

It is worth mentioning that hydro sources produce near zero carbon emissions. It is environmentally sound and an eco-friendly source of energy. Hydropower is an attractive energy source as it is renewable with minimal operational emissions of greenhouse gases (Iddrisu, 2014). However, climate change with its resultant erratic rainfall patterns has threatened its sustainability. Changes in the amount and timing of river runoff, coupled with increased reservoir evaporation will have significant impact on the production of hydroelectric power world-wide. This implies that over reliance on it to ensure security of electricity supply in Ghana will be problematic in the long run.

Another significant energy source that the country relies heavily on is thermal. Thermal sources of electricity generation are principally derived from gas and light crude oil. The VRA's thermal generation capacity is 922 MW at Aboadze while the independent Power Producers have a total capacity of 310 MW, comprising Sunon Asogli (200MW) and CENIT (110MW). Insufficient and unreliable gas supply as well as the cost of the light crude oil is a major hindrance to the thermal electricity generation in Ghana. The Volta River Authority uses about 3 million dollars per day to produce thermal electricity using light crude oil (Iddrisu, 2014). Ultimately the cost is definitely passed on to household and corporate consumers.

There is also a huge potential for electricity generation from renewable sources (energy source that can be replenished in a short period of time). They include solar energy (which comes from the sun and can be turned into electricity and heat), wind, geothermal (from inside the earth), biomass (from plants), hydropower and ocean energy (from water). They are economically affordable, environmentally sound and their operating cost is minimal even though they have an initial huge capital expenditure. Renewable Energy Technologies (RETs) have held promise for Ghana's development for many years. According to the Energy Commission (EC) of Ghana in their 2006 report, the government is aimed at having 10% Renewable Energy (RE) in its energy mix by 2020. However, efforts to make this promise a reality have not generally been successful. The deployment of the renewable sources will alter and boost the country's energy generation mix.

Each source of power generation has its own advantages and disadvantages in terms of affordability, environmental soundness and economic efficiency (IEA report, 2013). Therefore, for the country to meet its increasing electricity demand, the country has to diversify more of its electricity generation sources by incorporating RE into the current mix in order to have secure, affordable and uninterrupted energy supply.

1.2 Problem Statement

In recent times, there has been hue and cry about the energy (electricity) supply in Ghana, whether domestic or industrial. There has been increase in the use of electricity and petroleum products due to changes in the life style of the people such that they prefer, for example, to use electric iron instead of box iron, microwave oven instead of a stove, washing machine instead of washing with the hand etc because of the convenience in terms of saving in time and effort.

Ghana‘s electricity demand has been estimated to be growing at a high rate of about 10% per annum over the last ten years (Essah, 2011). This is due to the relatively high population growth, economic aspiration of the country, and the extension of electricity to rural areas. Electricity supply, in the contrary, has been unable to meet the demand due to high dependency on rain-fed hydro-power plants, which started operating in 1965 and currently account for about 70% of the total installed capacity (Iddrisu, 2014). Within the last 28 years, climatic change and draught have caused the nation to experience some major power crises. The climate change has resulted in low water inflows into the Volta Lake and thus has reduced power generation from hydro-power systems.

To complement the hydro-power systems, the Government in 1997 installed thermal plants based on light crude oil. However, the high crude oil prices on the international market in recent times have made the operation of these plants very expensive. Small Solar and wind generation exist in some sectors, but potentially large-scale development is not yet available to solve the current frequent power outages experienced by the country.

Poor electricity supply as well as frequent power outages poses a threat to economic development. It restricts economic growth and development, as well as the socio-economic welfare of the people and contributes to low productivity and poor competitiveness of the manufacturing sector in the country. Inadequate and unreliable power imposes a variety of costs on Ghana‘s economy.

The existing fuel mix for grid power generation in Ghana may not be able to securely meet the future supply requirements for transforming the Ghanaian economy into a middle income status. A viable alternative to avert supply disruptions is to explore and increase other energy sources such as the incorporation of RE, such as solar, wind, small hydro and biomass into the current energy mix. This research, therefore, seeks to investigate the possibility of incorporating RE sources into the country's energy mix in terms of finding an optimal cost efficient and economical way to do so.

1.3 Objectives of the Study

The main objective of this study is to find a minimum cost of investment in RE sources, specifically in Hydro, Wind, Solar and Biomass, that will meet projected demand levels in specific time periods in the future and ensure a modest (10%), (20%) or (30%) incorporation of these renewables.

1.3.1 Specific Objectives

The specific objectives are:

(i) To identify a suitable cost model that incorporates RE sources.

(ii) To model the energy mix problem as an optimization.

(iii)To determine optimal energy supply levels that incorporate 10%, 20% and 30% RE into the current energy supply mix.

(iv)To make recommendations on the basis of the results for Ghana's energy sector.

1.4 Research Questions

The research questions envisaged in this study are the following:

(i) What suitable cost model incorporates RE sources in our supply mix?

(ii) Can the problem be modeled as an optimization?

(iii) What supply levels of RE incorporation into the current energy supply mix will meet projected demand levels in the future at minimum investment cost?

(iv) What recommendations can be made on the basis of the results for Ghana's energy energy sector?

1.5 Significance of the Study

The results of this study will be significant to Ghana's development as the study intends to come out with a model that incorporates RE in the country's current energy mix and optimizing the model for minimum cost of investment.

The results of the study could also be used by VRA, ECG and other electricity companies in determining the best optimal energy mix that will meet the demands of consumers and minimizes total cost of electricity production in Ghana.

The findings of this research would add to the store of knowledge on the subject and serve as a basis for further research in the electricity generation sector in Ghana.

1.6 Justification of the study

According to the Energy Sector Strategy and Development plan (2010), the government of Ghana is committed to have 10% renewable sources in its energy mix by 2020. To reach this goal, in November 2011, Ghana's Parliament passed the Renewable Energy Act, providing the legal and regulatory framework necessary for enhancing and expanding the country's renewable energy sector.

In Ghana, it is expected that producing electricity from renewable energy sources will be less costly than from thermal power plants, especially since the government is spending large amount of money for the supply of gas and crude oil.

The intent of this research is to find a minimum cost of investment in RE sources, specifically in Hydro, Wind, Solar and Biomass that will meet projected demand levels in specific time periods in the future and ensure a modest (10%), (20%) or (30%) incorporation of these renewable energy sources in our generation mix.

1.7 Organization of the study

The study is in five (5) chapters. Chapter One comprises of the Background of the Study, Problem Statement, Objectives of the Study, Research Questions, Significance of the Study, Justification of the Study and Organization of the Study. Chapter Two is on Literature Review, which takes stock of what has already been written on the topic in terms of theories or concepts. Chapter Three introduces the research methodology and the guideline for approaching the above mentioned research problem. It outlines the methods and tools adopted for achieving the main objective of this thesis. Chapter Four forms the presentation and discussion of results of the study. Chapter Five constitute the Conclusions and Recommendation of the study.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter discusses Linear Programming (LP) and the solution methods; it also reviews related works in the subject area, including the energy sector of Ghana.

Optimization or constraint optimization is the process of obtaining the best possible 'result' under the 'circumstance'. The result is measured in terms of an objective which is either to maximize or minimize, whilst the circumstances are defined by a set of equality and/or inequality constraints (Murtagh and Saunders, 1978).

Optimization originated from George Dantzig, a member of the United State Air Force who developed the Simplex method for solving constraint optimization problems in 1947. The essence of the algorithm is to provide an efficient method in solving programming problems in which the objective and constraints have linear structure. Since then, experts from a variety of fields especially mathematics, Operation Research, Economics etc. have developed the theory behind linear programming and explored its application (Lewis, 2008).

Linear programming which, is one of the most widely used techniques in solving optimization problems has found practical application in many facets of human endeavor. Examples are financial portfolios construction, transportation systems, manufacturing, Health etc; these are typical areas where LP analysis have been applied (Bazaraa et al., 2005).

Today, optimization comprises a wide variety of techniques from Operations Research, Artificial Intelligence and Computer Science, and is used to improve business processes. The word "Programming" in Mathematical Programming is of a different flavour than the "programming" in Computer Programming. In the former case, it means to plan and organize. In the latter case, it means to write instructions for performing calculations. Although aptitude in one suggests aptitude in the other, training in the one kind of programming has very little direct relevance to the other (Konno and Yamazaki, 1991).

2.1 Assumptions of Linear Programming (LP)

There are four main assumptions inherent in a LP model that must be taken into account in any application. They are: proportionality, additivity, divisibility, and certainty.

- **Proportionality**

This requires that the terms of the objective and constraint functions are directly proportional to the activity levels and this should hold over the entire ranges of the activity levels. There are many cases where this assumption may not hold strictly and may be used only as an approximation. Where even an approximation is unreasonable the problem may well require the use of nonlinear programming.

- **Additivity**

This assumes that there is no interaction between any pair of activity levels and that an activity level varies linearly and that for a given set of activity levels, the total contribution to the objective and constraint functions are the sum of their individual contributions. It is noted that the proportionality and additivity assumptions ensure the linearity of the objective and constraint functions.

- **Divisibility**

This assumes that an activity level can be divided into any fractional parts so that non integer values of the decision variables are permitted. This assumption also ensures the continuity of both the objective and constraint functions. Where this assumption is not the case, after solving the model, the variable values can be rounded to the nearest integer. There are cases, where doing this may be unreasonable, such as with very sensitive models. In such cases one would have to resort to the use of integer programming which is a variant of LP.

- **Certainty**

This assumes that all the parameters of the model are known precisely. In real problems this is usually not the case. A reasonable approximation or estimate of their values would have to be used under such circumstances. A sensitivity analysis can reveal those values of the parameters that ensure that the model is stable.

Integer Linear Programming (ILP): is one aspect of LP techniques with the additional requirement that some or all of the decision variables are integer. An ILP where all the decision variables and possibly the objective function are required to be integer is called "all-integer linear program". However, when the word "integer" is dropped from model formulated in the context of optimization problems, it would lead to two kinds of models: (1) a model that result from dropping the integer requirements for the decision variables is called "Linear Programming Relaxation (LPR)" of the ILP and (2) model that restrict some but not all of the decision variables to be integer is called "Mixed Integer Linear Programming (MILP)"

2.2 Solution Methods

The Simplex method is a widely used algorithm for solving large scale LP problems in particular where ones geometric intuition falters and one has to rely on algebraic means in order to solve a LP problem. The graphical approach solves LP problems by identifying the extreme points of the feasible set and testing the objective function value at the extreme points. The one which yields the best value for the objective function is selected as the optimal solution. The Simplex algorithm does the same thing using purely algebraic means. The algebraic means is necessary in higher dimensional (i.e. $n \geq 3$) due to our inability to perceive the feasible region or the objective function geometrically. In higher dimension the objective and constraint functions are not line segments but hyper-planes (a geometrical concept of a plane in higher dimension) and the feasible region not a plane polygon but a simplex which is a region bounded by hyper-planes (Catherine, 2008).

The Simplex algorithm may be applied in two phases, namely phase 1 and phase 2.

Phase 1 produces the information that the LP is infeasible or furnishes an Initial Basic Feasible Solution (IBFS).

Phase 2 begins with an IBFS and search for another Basic Feasible Solution (BFS) with a better objective function value when the optimization test is not passed. The search continues until the optimality test is passed and has an optimal solution obtained or until it is clear there is no bound solution (Bazaraa *et al*., 1990).

The Simplex algorithm is described by the following steps:

Step I: Putting the LP in standard form.

Step II: Finding an initial basic feasible solution (IBFS)

Step III: Checking whether the IBFS is optimal

Step IV: If IBFS is not optimal, find a new BFS with a better objective function value

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

The Simplex method is an iterative search algorithm for large LP problems, starting from the initial ("origin", where all $x = 0$) and moving toward adjacent "corner" points at the direction in which improvement on objective function value is maximized. If one "corner" point solution is better than all adjacent "corner" point solution, it is "optimal". The Simplex algorithm examines a finite number of basic feasible solutions (BFS) for optimality. For large size problems where the number of BFS's can be very large, the algorithm examines a subset of the BFS for optimality. Even so, for very large size problems, the subset of BFS to examine could still be very large. Software packages of the Simplex algorithm abound today and can be implemented on a computer.

There are numerous method used in solving integer linear programming problems but the most common one is the "Branch and Bound (BB or B&B)" method (Taha, 2011). This method is used to deal with problems either manually or computationally depending on the complexity of the problem before the analyst. The concept of the BB is to divide (branching) the originally large problem into smaller sub problems and bounding the best solution in the subsets. The algorithm consists of a systematic enumeration of all admissible solutions, where large subsets of fruitless candidates are discarded by using upper and lower estimated bounds of the quantity being optimized (Bazaraa *et al*., 2005).

The algorithm is as below:

Step I: Solve the problem without integer restrictions,

Step II: If the solution is integer, then the algorithm ends,

Step III: If the solution is not integer, then the feasible region is divided by adding constraints restricting the value of one of the variables that was not integer valued, Step IV: Bounds on the value of the objective function are found and used to help determine which sub-problems can be eliminated and the optimal solution is found,

Step V: If a solution is not optimal, a new sub-problem is selected and branching continues until an optimal solution is found (Lewis, 2008).

2.3 Review of related works

Gyamfi et al. (2015) provided a review of the assessed potential renewable energy resources, their current exploitation status, and their potential contribution to the electricity supply of the country. It also presented the barriers to their utilization and the existing policy and regulatory instruments to overcome those barriers. The results showed that Ghana has several RE sources, such as wind, solar PV, mini hydro and modern biomass that can be exploited for electricity production. A review also shows a great potential for RES generation to increase substantially over the next decade, looking at the government commitment and legal frameworks that are being put in place.

Essah (2011) examined the energy generation and consumption pattern in Ghana. According to Essah, electricity consumption in Ghana is estimated to be increasing by 10% per annum due to the demand from the growing population. The research was carried out using three key techniques; review of literature, empirical studies and modeling. The results presented suggest that, current annual installed capacity of energy generation must be increased in order to cope with the growing demand. It would also give access to the entire population as well as support commercial and industrial activities for the growth of the economy. The paper however suggested further research into the subject area.

Umar (2010) studied the financial assessment of the investment potential of renewable energy electricity production in Ghana. Ten coastal areas were identified in his study to be viable sites for Wind Electric Conversion Systems (WECS). Solar resources were found to be excellent throughout the country with the three Northern Regions having the highest solar insulation and hours of sunshine. The study also revealed that the country is naturally endowed with hydro power potential with many sites identified as having the potential of being tapped. Using Total Life Cycle Costing (TLCC) and Levelized Cost of Energy (LCOE) produced, it was found that conventional means of generating electricity vis-à-vis Diesel Generator (DG) has the least TLCC and LCOE when the cost of CO2 is assumed not levied against the DG and carbon credit not given to Renewable Energy Technologies (RETs). On the other hand if the cost of carbon was taken into consideration, the WECS was ranked first in least TLCC and LCOE while the DG and the hydro power are competitive. The major conclusions drawn from the study were that; the WECS and hydro power have the potential of being used to generate electricity in Ghana but will need government's support in the form of renewable energy policies that will provide loans of low interest to RETs.

Henry et al. (2010) presented an analytical model for wind power investment. The model was formulated as mixed integer programming with cost minimization as objective. The study also resorted to finance literature for models that will be able to systematically characterize return and risk on the investment. Real option theory was chosen and a primitive function defined for the fuel cost that will be saved as the revenue for the wind power project. Subsequently the real project was described as a contingent claim on the stochastic fuel prices. Theoretical valuation of the project was thus given by the solution of a partial differential equation. The formulation avoided the ambiguity in analyzing wind power investment based on non-market-based tariffs, but focuses on the welfare to the system as a whole.

Finally a hypothetical scenario of carbon emission price was included to demonstrate the incentive it could offer to renewable generation.

Bonacina (2013) looked at the construction of optimal electricity generation mix portfolio in Italy. In his analysis, he considered an electricity producer who can choose to invest both in renewable and conventional sources. Portfolios were built based on the Net Present Value (NPV) generated by the investment in a particular technology. The study illustrated a general model based on Monte Carlo simulations for the computation of the NPV generated. The model was applied to compute the optimal generation mix in Italy. The results obtained shows that, without incentives, conventional technologies dominate the optimal production mix.

Muhammad et al. (2012) presented a paper on the topic; Optimization Model using Wien Automatic System Planning - IV (WASP-IV) for Pakistan's Power Plants Generation Expansion Plan. The paper introduced novel framework for the modeling of hydro and thermal power plants generation system expansion plan for Pakistan. The modeling was achieved by using WASP-IV model which consists of seven modules. Each module determines different outputs with their respective inputs. An optimized model was prepared for the hydro and thermal power plants. To carry out the research, a methodology was selected with respect to the generation expansion constraints. The collected and forecasted data was given to the WASP-IV modules. They generated output results until the optimization was achieved through the help of screening curves and dynamic programming. The optimized results were analyzed and a generation expansion plan was prepared.

Vahakn and Leila (2014) examined an optimal RE mix of the power sector for Lebanon. The study incorporated the capacity potential of three renewable technologies (Solar, wind and Hydro) with the assumption of meeting an estimated electricity demand by 2020 in a number of scenarios. The study first converses with simulation optimization models with a cost criterion to determine the optimal supply mix from RE according to two scenarios; 12% target and a more ambitious 20% share.

Financial analysis was implemented as to estimate the total cost to the government and the economy assuming two – thirds of energy supply from combined Cycle Gas Turbine (CCGT) plants with either HFO or natural gas, whiles incorporating the optimal 12% and 20% RE mixes. Results showed that the option of supporting a feed - in tariff scheme to encourage renewable investments from the private sector will be less costly to the government as compared to additional investments in conventional sources of energy.

Reinhard et al. (2010) Studied the Optimization of E.ON‘s Power Generation with a Special focus on renewables. The main goal of the research was to analyze the efficiency of E.ON's current combination of existing power generation portfolios in different market units, compared to the optimal (either minimum risk or maximum return) portfolios, with a particular focus on the role of renewable energy technologies and the situation in Germany, Sweden, and the United Kingdom. Fuzzy portfolio selection optimization models were used in the study. Results from the portfolio analysis of E.ON's power generations in Germany, Sweden, and the United Kingdom considering annual return as well as net present value as selection criteria show that the efficiency of E.ON's power generation mixes could indeed be improved by adding some more renewable technologies to the portfolios

Saeko et al. (2010) developed an optimal power generation mix model. The model, under various assumptions, power generation capacity and its operation were specified through the minimization of total power generation cost, mainly consisting of facility cost and fuel cost. Linear Programming method was adopted. The study stated that, in future power generation mix, solar and wind power were expected to become the center of renewable power supply sources. An analysis of the model confirmed that wind power generation when effectively adopted will lead to the reduction of carbon dioxide.

Christian (2014) looked at power generation scheduling problem of Volta River Authority of Ghana which was formulated as Mixed Integer Linear Programming and the resulting model tested using real data obtained from the Authority. The test results showed that daily load demands could be met at a minimum cost. Furthermore, the marginal cost of production of power obtained from the dual of the MILP model provided insight into the appropriate Tariff that is reasonable for the power producer to charge consumers. According to the study, the hydroelectric and thermal power plants, Akosombo and TAPCO were required to contribute substantial amounts of power to the power produced in every period of the day and thus ware critical to the power generation operation.

Martin and Diesendorf (2009) dealt with optimal thermal mix in electricity grids containing wind power. A probabilistic model was used to calculate the optimal mix of thermal base and peak load plant in an electricity grid with zero storage and with different amounts of wind power capacity. It was found that when wind power capacity is introduced into an electricity grid and a new optimal mix of base and peak conventional plant is obtained with the same overall grid reliability, less fuel is burnt in the conventional plant and less conventional capacity is required. In other words, wind power capacity saves fuel and has a capacity credit.

Zhou (2010) studied the effect of increasing wind power output to 20% of energy generation on Real-time Energy Markets. The study first modeled the unit commitment optimization problem for the Day-ahead Market and then simulated the Real-time Market portfolio rebalancing using actual data for generator parameters and hourly demand. Results showed that additional wind reduces costs with 70% efficiency. The research concluded that wind technology is the most reliable and abundant form of renewable energy generation currently available. Its importance will rise drastically and become an integral part of the power market over the next few decades. The research however suggested that, as solar becomes more viable and as natural gas storage makes gas generation less expensive, further studies could be carried out to see their effects on the Energy Market by 2030.

Fernando (2011) used an extended unit commitment model to study how different penetration levels of renewable energies (wind and solar) and curtailment options affect the optimal generation capacity and the cycling regime of the thermal units. The model starts from a set of plants that could be potentially built and decides on the optimal capacity mix, taking into account operational constraints and reserves requirements. The results indicated that greater levels of penetration of renewables require a smaller capacity of nuclear power and a larger amount of gas-fired power plant. The study also showed that wind curtailment is a valuable source of operational flexibility since, to a certain extent, it avoids the need to install other more expensive and more polluting units.

2.4 Power situation in Ghana

A cursory look at the current power situation in Ghana, against the background of the challenges many Ghanaians face in accessing constant and reliable electricity supply for domestic and industrial activities, should reveal that the load shedding exercise we experienced during the first half of 2013 and which is forecasted to persist in the medium term beyond 2015 though on a reduced scope, is primarily a self-imposed one (Theo and Festus, 2014). This is largely because of the State's inability to provide the right incentives and a misaligned regulatory structure, which together have failed to attract the much needed investments into an electricity supply sector still dependent on legacy infrastructure.

Between 1989 and 1990, the government committed itself to raise access to electricity for all parts of the country over a 30-year period under the National Electrification Scheme (NES). The programme established projects that were driven towards the provision of electricity access to the northern parts of the country, which then un-electrified. In 1990, the VRA rehabilitated and re-commissioned the Tema Diesel Generating Station which has a capacity of providing supplementary generation of 30 Megawatts (MW), thereby raising the total capacity of electrical power to about 1,102 MW.

Between 1990 and 2001, electricity consumption grew from 4,457 Gigawatt – hour (GWh) to 6,033 GWh at an average rate of 9.42% per annum, excluding the Volta Aluminum Company (VALCO), whose Aluminum smelter at Tema used up around 40% of total electricity supply in the mid-1990s (EC report, 2004). The increase in consumption, as compared with the population growth of 2.67%, was due to a remarkable increase in electricity access starting from 28% in 1988, to 32% in 1992 and to 43.7% in 2000 (Akuffo, 2007). Electricity access rate of Ghana was estimated to be 54% in 2007 and 55% in 2008, making Ghana the third highest in sub-Saharan Africa, after Mauritius and South Africa (World Bank Report, 2009).

Despite the increased access to electricity nation-wide, there exists a large disparity in access between the urban and rural areas as reported by the Ghana Statistical Service. This contrast was revealed in a more upsetting mode in the year 2006 in which Ghana experienced a power crisis due to low electricity generation capacity. The crisis prompted the government and VRA to review their long-term electricity policy in terms of the electricity generation mix required for long term national investments. Momentous investments have since been made in thermal plants and system upgrading with the completion of VRA‗s 126 MW Thermal 1 Project. Several independent power projects are also at various stages of advancement, all at Tema most of which have been completed (Akuffo, 2007). The 400 MW Bui Power plant by the Chinese (Sino Hydro) has also just been completed. There is the likelihood of work starting soon on the Western rivers (Theo and Festus, 2014).

In 2011, the total grid electricity generated in the country was 10,167 Gigawatt-hour (GWh). The load at peak periods on the transmission grid was 1,665 Megawatts (MW) and the grid system peak was 1,745 MW. In 2012, the total grid electricity generated in the country was 12,164 Gigawatt-hours (GWh) and for 2013, the total estimated electricity needed for the country was in the range of 13,667 - 15,794 GWh. Peak load on the transmission grid for 2012 was 1,729 Megawatts (MW) and the total peak on the overall grid system was 1,871 MW. For 2013, Ghana‗s peak load and the total system peak on the grid transmission system was about 1,800 MW and 1,900 MW respectively (EC, 2012).

In 2013, the total grid electricity generated was 12,874 GWh about 6% more than in 2012. Peak load on the transmission grid was 1,791 MW; 2.7% more than in 2012 and the total system peak on the transmission system was 1,943 MW; 3.8% more than in 2012.

In 2014, the total electricity requirement was 15,725 GWh. Peak load ranged between 1,900-2,200 MW and the total system peak on the grid transmission system was within 2,200 -2,300 MW.

According to the 2014 report of EC, the generally tight economic conditions coupled with the prevailing relatively high electricity costs are likely to limit the total electricity demand to between 14,571-15,351 GWh in 2015. The grid electricity available for supply based on the generation capacity would be within 13,011-13,971 GWh. The projected electricity demand within the constraints of the limited available supply means that there is bound to be significant supply shortfalls any time a power plant is turned off even for scheduled maintenance (EC, 2014).

Shot in energy supply in 2014 based on the projections of EC was between 1,700 -2,480 GWh which translates into 240–330 MW thermal plant equivalent. A total of about 700-800 MW additional thermal capacity equivalent would therefore be needed to cover the shortfall and a minimum of 20% reserve margin for 2015. Annual capacity shortfall is estimated to be between 200MW -250 MW. The challenge however is securing adequate supply of gas which is a less expensive fuel to make electricity production cost relatively affordable.

As Ghana seeks to expand its industrial base in the quest to transform its economic fortunes, a reliable supply of energy, primarily electricity supply, will be the crucial factor and catalyst for industrial development which in the process will lift many out of poverty. The 2010 Wholesale

Power Reliability Assessment report estimated that Ghana loses between 2 to 6% of GDP annually not including a number of indirect costs of lost economic output due to insufficient whole sale power supply (Theo and Festus, 2014). Thus, the economic costs of inadequate power supply cannot be underestimated.

The promised changes of the liberalized electricity markets as part of the IMF-World Bank Structural Adjustment Programmes, which started in the late 1990s and which aimed to bring increased private sector investments and expand capacity are yet to be realised due to an inefficient setup of the regulatory structures compounded by low tariff pricing options and gross wastage leading to sub-optimal outcomes for both consumers and the utilities companies almost 20 years down the line (Theo and Festus, 2014).

2.4.1 The Current Generation Mix

According to the Energy Sector Strategy and Development plan (2010), the government of Ghana is committed to have 10% renewable sources in its energy mix by 2020. To reach this goal, in November 2011, Ghana's Parliament passed the Renewable Energy Act, providing the legal and regulatory framework necessary for enhancing and expanding the country's renewable energy sector.

It is acknowledged that renewable energy investments incur high costs on governments, typically with large up-front capital cost (Vahakn *et al.*, 2014). In Ghana however, it is expected that producing electricity from renewable energy sources will be less costly than from thermal power plants, especially since the government is spending large amount of money for the supply of gas and crude oil.

VRA is the major power generation company, solely owned by the Government of Ghana and established in 1961 by an Act of Parliament. It forms the first arm of the recently restructured electricity generation, transmission and distribution chain in Ghana. VRA combines hydro, thermal and solar plants to generate electricity for supply to the local and export markets. The local market consists of the Electricity Company of Ghana (61% of market consumption), the mines, and industrial establishments (which purchase electricity directly from VRA) with the export market comprising Communauté Electrique du Benin (CEB) (for the Republics of Togo and Benin) and SONABEL (Burkina Faso) (VRA Profile, 2015).

VRA reaches its customers and neighboring countries through GRIDCo's transmission system. This transmission system covers the entire country and is connected with the national electricity grids of Compagnie Ivoirienne d'Electricité (CIE) of La Cote d'lvoire, (CEB) of Togo and Benin and SONABEL of Burkina Faso. These interconnections now serve as part of the arrangement under the West Africa Power Pool (WAPP) (VRA Profile, 2015).

The Northern Electricity Distribution Company (NEDCo), a subsidiary of VRA, undertakes the distribution function in northern Ghana covering the Upper East, the Upper West, Northern and Brong Ahafo regions, as well as parts of the Ashanti and Volta Regions. NEDCo was developed as an integral part of a larger scheme, designated the Northern Electrification & System Reinforcement Project (NESRP) to extend the national electricity grid to northern Ghana (VRA Profile, 2015).

Historically, the Electricity Supply Industry (ESI) in Ghana has been dominated by hydro power, which accounted for all generation until the late 1990s. That situation has now changed and since the end of 2010, Ghana's total installed thermal generating capacity has almost equaled the existing hydro generation capacity.

The VRA's hydroelectric power generation plants, the Akosombo Hydroelectric Power Plant and Kpong Hydroelectric Power Plant are situated in the Eastern region. The thermal plants are situated mainly in Tema and Takoradi. In addition to those owned by the VRA, Independent Power Producers (IPPs) support the electricity supply market.

There are currently nine (9) main operating power generation facilities in Ghana, as detailed in Tables 2.1 and 2.2 with a total installed generation capacity of 2,846.5MW, of which VRA contributes about 75%.

Table 2.1: Main operating power generation facilities in Ghana

Generation Facility/ plants	Installed Capacity (MW)	Installed Capacity (%)	Type	Fuel Type
Akosombo	1,020	35.83%	Hydro	Water
Kpong	160	5.62%	Hydro	Water
TAPCO (T1)	330	11.59%	Thermal	LCO/Gas
TICO (T2)	220	7.73%	Thermal	LCO/Gas
T3	132	4.64%	Thermal	LCO/Gas
TT1PP	110	4.43%	Thermal	LCO/Gas
TT2PP	50	1.79%	Thermal	DFO/Gas
MRP	80	2.80%	Thermal	DFO/Gas
Solar	2.5	0.09%	Renewables	Solar
Total	**2,104.5**	**74.49%**		

Source: VRA, Power Outlook2015

Table 2.2: Installed Capacity of IPPs and other Plants

Plants	Installed Capacity (MW)	Installed Capacity (%)	Type	Fuel Type
Sunon Asogli	200	7.03%	Thermal	Gas
CENIT	126	4.43%	Thermal	LCO
Bui HEP	400	14.05%	Hydro	Water
Total	**726**	**25.48%**		
GHANA'S TOTAL INSTALLED CAPACITY: 2,830.5				

Source: VRA Power Outlook, 2015

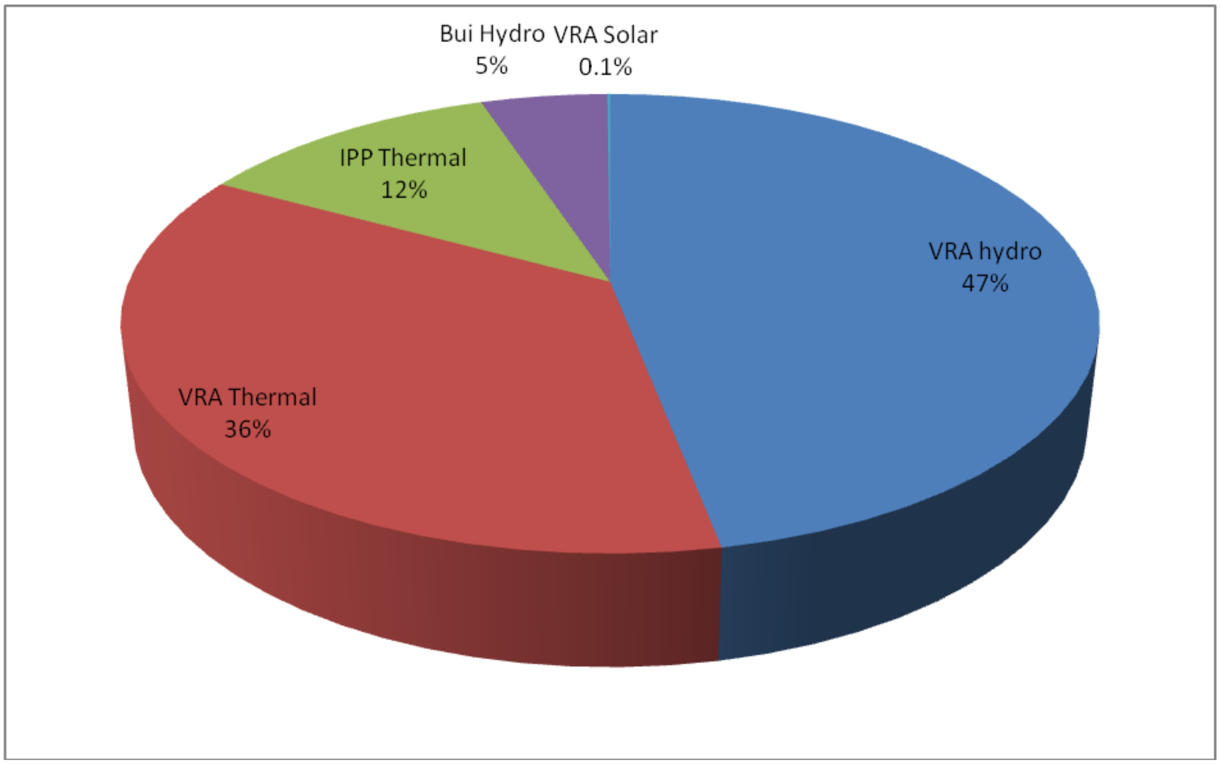


Figure 2.1: Ghana's Effective Installed Generation Sources as at April, 2015
Source: VRA Power Outlook, 2015

Figure 2.1 shows the current installed energy generation sources in Ghana as at April 2015 with the largest share of 47% coming from VRA Hydro whiles the smallest share of 0.1% is from solar.

2.5 Economic Growth and Electricity Demand in Ghana

It is estimated that approximately 72% of the Ghanaian population has access to electricity. Various studies have established a strong relationship between real GDP growth rate and electricity consumption. Other variables include the population growth rate and the Government of Ghana's (GoG) program to increase access to electricity in the country as well as initiatives to improve efficiency in energy use. With Ghana's population growth at 2.3 per cent per annum and GDP growth at 5.5 per cent per annum, electricity demand is projected to grow over the next 10 years (EC, 2009).

Alternative Energy Africa (2009) estimates Ghana's rate of increase in demand for electricity at 10 to 15% per annum over the last two decades. It is projected that the average demand growth over the next decade will be about six percent per year. As a result, consumption of electricity will rise years to come. The projected electricity growth assumption has profound economic, financial, social and environmental implications for the country. The aspirations of developing countries for higher living standards can only be satisfied through sustained development of their electric power markets as part of their basic infrastructure. Electricity demand will grow much faster than overall economic growth or than population growth because continuing urbanization will allow newly urbanized segments of the population to expand their electricity consumption manifold (EC, 2006).

Urbanization in Ghana increased from around 40 percent in 2000 to about 55 percent in 2012 and is expected to increase to 60 percent by 2020. Residential demand may increase between 7,000 and 13,000 GWh by 2020 depending on the rate of economic growth and urbanization. The residential sector is not the only segment expected to grow; commercial and industrial consumption may also grow between 3,000 to 10,000 GWh by 2020 (EC, 2012).

The EC and the VRA have produced electricity demand forecasts with a growth rates in the range 6–7%. Table 2.3 and Figure 2.2 show the electricity demand forecast.

Table 2.3: Electricity projections for three economic scenarios. 2006 – 2020

GROSS ELECTRICITY SUPPLY REQUIREMENT* in Gigawatt –Hours (GWh)						
Year	**Business-as-usual, or Low economic growth**		**Moderately high economic growth**		**GPRS High economic growth**	
	Without Valco	***With Valco***	***Without Valco***	***With Valco***	***Without Valco***	***With Valco***
2006	5,900	8,478-9,156	6,886	9,022	7,804	9,900
2007	7,282	9,920-10,598	9,143	12,100	11,004	13,960
2008	7,666	10,862-11,540	9,618	13,000	11,570	14,900
2009	8,073	11,675-12,354	13,161	16,660	18,248	21,540
2010	8,502	11,168-12,846	13,848	17,484	19,194	22,500
2011	8,904	12,626-13,304	14,488	18,243	20,072	23,370
2012	9,325	13,108-13,786	14,600	18,500	20,144	24,650
2013	9,768	13,615-14,294	14,990	19,500	20,210	24,770
2014	10,233	14,150-14,828	15,676	20,200	21,120	25,620
2015	10,721	14,730-15,408	16,398	20,900	22,074	26,600
2016	11,234	15,321-16,000	17,155	21,660	23,077	27,600
2017	11,773	15,944-16,623	17,951	22,598	24,130	28,630
2018	12,340	16,600-17,280	18,787	23,613	25,235	29,948
2019	12,934	17,291-17,970	19,666	24,682	26,398	31,394
2020	**13,560**	**18,036-18,714**	**20,590**	**25,815**	**27,620**	**32,915**

Source: Energy Commission,2006

By the projections shown in Table 2.3, it means that demand for electricity in the year 2020 will be 13,560GWh if Valco is not in operation. But it will however, increase to the range of 18,036GWh to 18714GWh in the low demand growth scenario. In the moderately high and high economic growth scenarios, with Valco in operation, electricity demand will increase to 27,620GWh and 32,915GWh respectively. This is an indication that other generation sources need to be exploited in other to meet the growing electricity demand.

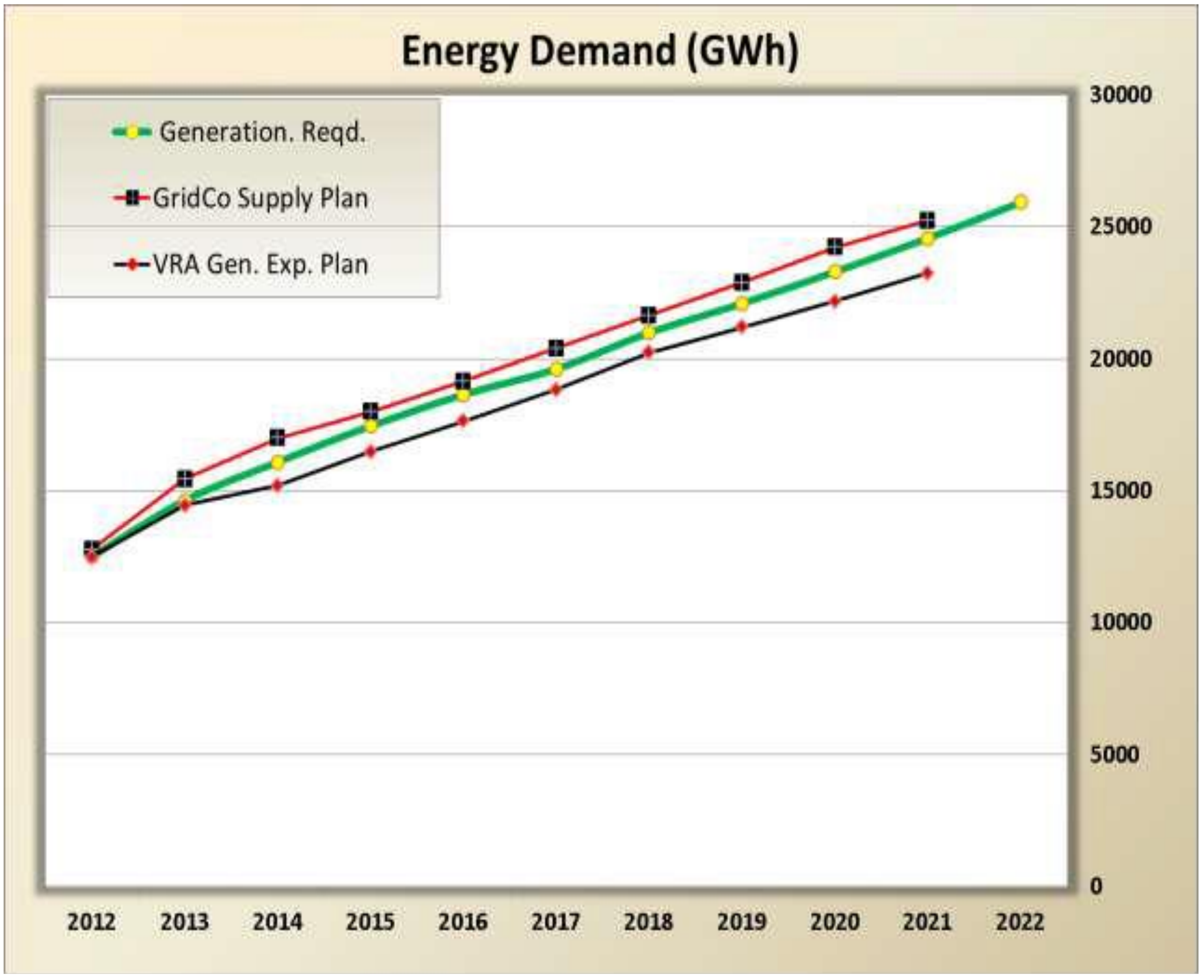


Figure 2.2: Projected energy demand
Source: Volta River Authority

Clearly, with the Ghanaian economy growing, increasing urban populations will consume more electricity. In order to meet this increasing demand, new power generation as well as transmission and distribution facilities will have to be built.

Governments have been pursuing a national electrification policy. Still, more than half of the population remains without access to grid-based electricity (EC report, 2006). It is very expensive to build long-distance transmission lines to serve small communities, especially when these communities are relatively poor and cannot afford to pay rates high enough to cover the cost of these services. Moreover, there is weak or no evidence of increased economic activity in communities that benefited from the national electrification scheme. Smaller scale and locally installed generation systems using solar panels, batteries and the like can be more affordable. Nevertheless, rural electrification will continue to be a challenge for Ghana unless other alternative sources of energy generation such as Renewable Energy Technologies (RETs) are considered.

As part of the expansion plans for meeting the supply requirements of the country, Ghana Energy Commission in July 2006 came out with three alternative expansion plans. These include;

- Option One: An expansion plan based primarily on natural gas and with renewable energy making a 10 percent contribution of installed capacity by 2020.

- Option Two: An expansion plan based on natural gas, Bui hydropower project and 10 percent renewable energy contribution of installed capacity by 2020.

- Option Three: An expansion plan based on natural gas, Bui Hydropower project, nuclear power and 10 percent renewable energy contribution of installed capacity by 2020.

Generation mix of the expansion options by installed capacity is shown in the Table 2.4

Table 2.4: Generation mix of the expansion options by installed capacity

Average generation mix by installed capacity of the expansion plans in %			
	Option 1	**Option 2**	**Option 3**
Hydropower	39 - 41	46 - 49	44 - 46
Thermal	51	43 – 46	41 – 43
Nuclear	0	0	3 – 8
Renewables	8 – 10	5 – 11	7 – 8

Source: EC report, 2006

A 10 percent contribution of renewable energy to the generation mix is the optimum proportion that will maintain the average generation costs of all the options at about the same level (EC, 2006).

The inclusion of renewables (excluding the traditionally large hydro plants such as Bui), was to start with a share of about 5% by 2008 increasing to about 9% by 2015 and eventually up to 10% by 2020. But this is yet to see the light of day since only 0.09% of solar is incorporated.

Based on VRA's 2013 to 2025 capacity demand and supply balance, and in line with Ghana's power sector reform and major policy objectives, the country's current total installed generating capacity requires to be increased to 5,175 MW by 2023 in order to address the current power shortages, ensure an adequate supply of electricity, meet the country's forecast growth in demand requirements and improve the quality of service and reliability of the power system.

The projected shortfall in generation capacity is expected to be filled by both VRA and IPP's who have both embarked on various activities to expand power supply and infrastructure. In this regard, VRA is focusing on a number of power expansion projects and new projects, designed to ensure electricity availability and accessibility in the short-to-medium term. These include renewable energy (wind, hydro and solar) and combined cycle power plants, as detailed below.

- ✓ Conversion of the 220 MW Takoradi International Company (TICO) Thermal Plant into a 330 MW combined cycle plant (construction commenced in 2012);
- ✓ Development of two wind projects with a total capacity of 150-200 MW;
- ✓ Development of 100 MW of solar energy;

- ✓ Commencement of feasibility studies for the development of 140 MW of hydro dams at Pwalugu and Juale in the Northern Region;
- ✓ Development of a 200MW Thermal Plant located at Kpone, near Tema, by 2014;
- ✓ Development of biomass sources of power with Clark Sustainable Resource Development;
- ✓ Expansion of the existing 110 MW single cycle Tema Thermal Power Plant (TT1PP) into a 330 MW combined cycle plant;

The general relatively tight economic conditions coupled with the prevailing relatively high commercial and industrial tariffs could cause total electricity demand to slump from the predicting range of 15,676 -15,932 GWh (*with VALCO operating at one potline*) to between 14,571-15,351 GWh in 2015 (EC ,2014).

The closeness of the gap between the electricity requirement by the economy and available supply means, there is bound to be significant shortages with likely accompanying load shedding anytime any of the power plants is shut down for routine maintenance.

2.6 Overview of Renewable Energy Technologies in Ghana

Renewable Energy Technologies (RETs) have held promise for Ghana's development for many years. However, efforts to make this promise a reality have not generally been successful. During times of energy crises–when there is prolonged drought in the catchment areas of the Volta Dam, or when the world oil prices increase sharply–there is sudden interest in RETs as a possible alternative to our dependence on the grid. This interest wanes as rapidly as the crisis is resolved. The cycle has been repeated most notably during the 1997 electricity shortfall (Attachie, 2013).

Renewable Energy Technologies are methods of harnessing energy for human use in such a way that the source of energy is not depleted over time. That is they are those that are not depleted as they are consumed. The wind, sun, moving waters (hydroelectric), water heated in the earth (geothermal) and vegetable matter (biomass) are typical renewable energy sources for electricity. According to EC 2006 report, renewable energy is economically competitive with the fuel fossils and would play an increasingly vital role in the power generation mix over the next century. The development of renewable energy and energy efficiency marks a new era of energy exploration in Ghana. The VRA intensified its effort at renewable energy development projects. Development work is progressing steadily on a number of renewable energy projects.

A Renewable Energy Law was enacted in December 2011, and a feed-in-tariff scheme is being developed to promote the exploitation of renewable energy sources like solar and wind. The government expects renewable energy sources to account for about 10% of the total primary energy mix by 2020 (EC report, 2006).

2.6.1 Hydroelectricity

Hydroelectricity is created as turbine generators are driven by moving water. Hydroelectric power is currently the largest producer of renewable energy in Ghana. Hydro generation accounted for 75.3% of the total supply of power. It is one of the major sources of base load electricity generation. Despite its high initial capital cost, hydropower provides one of the cheapest and cleanest sources of electricity.

There are 22 exploitable small and medium hydro sites in the country with total potential of 937MW, about 3,681 GWh of energy annually. Table 2.5 shows potential hydro sites in Ghana.

Table2.5: Medium Hydro Sites in Ghana

RIVER BASIN	POTENTIAL (MW)	ANNUAL ENERGY (GWh)
Black Volta		
Koulbi	68	393
Ntereso	64	257
Lanka	95	319
Jambito	55	180
	Total: 282	**1,148**
White Volta		
Pwalugu	48	184
Kulpawn	36	166
Daboya	43	194
	Total: 127	**544**
Oti River	90	405
Juale	**Total: 90**	**405**
River Tano		
Asuaso	25	129
Sedukrom	17	67
Jomoro	20	85
Tanoso	56	256
	Total: 118	**537**
Pra River		
Awiasam	50	205
Hemang	90	336
Abatumesu	50	233
Kojokrom	30	136
Total	**Total: 220**	**910**
Ankobra		
Nsueam	25	33
Breman	25	41
Mehami	50	63
	Total: 100	**137**
TOTAL POTENTIAL	**937**	**3,681**

Source: Volta River Authority

2.6.2 Wind Energy

Electricity can be created when the kinetic energy of wind is converted into mechanical energy by wind turbines (blades rotating from a hub), that drive generators. Ghana has some wind resources that could be tapped to supplement her energy requirements.

Over the past 20 years extensive assessment of wind energy potential in Ghana has been carried out and reliable data on wind is available at the website of the Energy Commission of Ghana. Indications are that the coastal belt of Ghana has good wind energy potential and the most economic exploitation based on current technology is at 50 metre-height with average wind speeds between 6.0 – 6.3 metres per second (m/s). The corresponding wind power density range from 185 - 210 Watt per square metre at 1.225 kilogramme per cubic metre (kg/m3) air density (Antonio, 2003).

Ghana has about 2,000MW of raw potential for wind energy as shown in the Wind Energy Resource Map of Ghana. It is currently reliably projected that over 300 – 400 Megawatt power can reliably be tapped to generate over 500 GWh per year to supplement the nation's energy needs. The wind direction in the country is predominately southwest (Antonio, 2003).

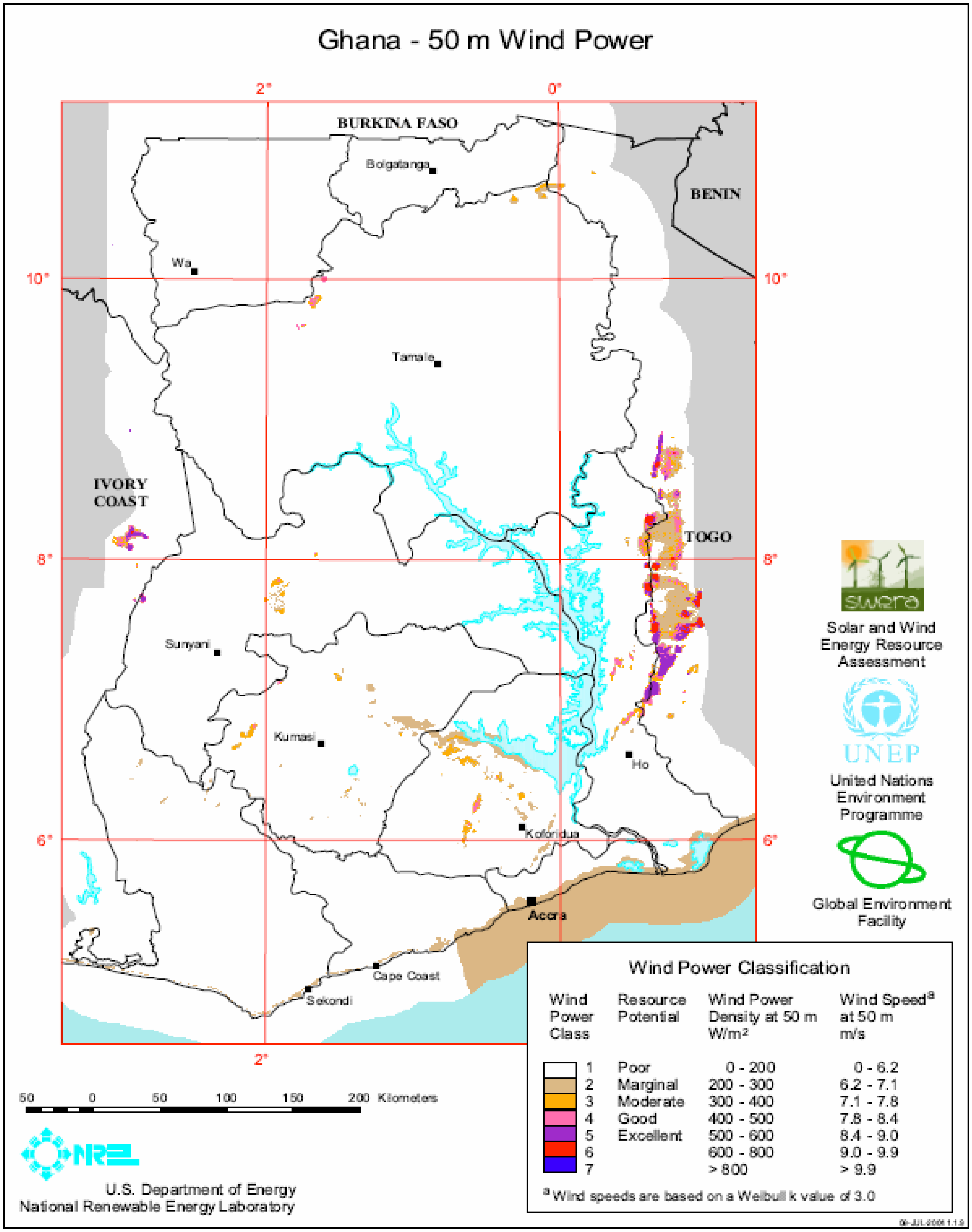


Figure 2.3: Wind Power Map of Ghana
Source: EC report, 2009

2.6.3 Solar Energy

By virtue of Ghana's geographical location in the tropics, solar radiation is available almost throughout the year. Solar resources in the country could be exploited for electricity generation and low heat requirements in homes and industries. Its utilization has however been limited owing to its comparatively higher cost. The Government of Ghana is committed to improving the cost-effectiveness of solar and wind technologies by addressing the technological difficulties, institutional barriers, as well as market constraints that hamper the deployment of solar and wind technologies (EC report, 2009).

The country receives on average 4.0 - 6.5 kWh/m2/day of solar radiation and sunshine duration of about 1800-3000 hours per year (EC, 2007). Solar radiation data demonstrate some geographical variation with the highest solar intensities occurring in the savannah zone and the lowest in the middle forest zone. The Solar Map of Ghana which gives a graphical presentation of the relative solar energy resource endowments across the country is shown in Figure 2.4.

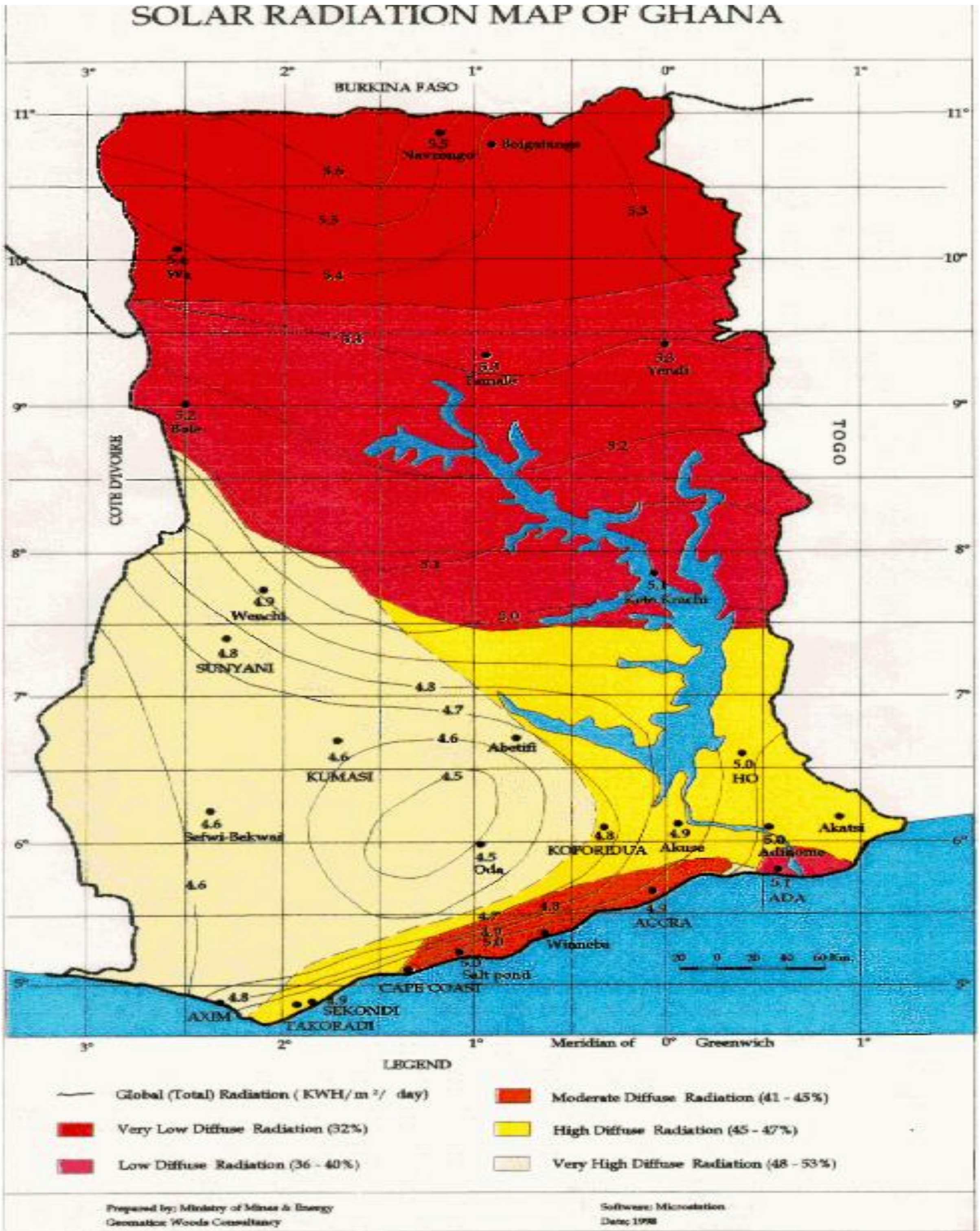


Figure 2.4: Solar Radiation Map of Ghana
Source: EC report, 2009

2.6.4 Biomass

Electricity can be created when various materials (like wood products and agricultural waste, or even crops grown for use in electricity production) are combusted. Ghana has some agricultural waste but there are no biomass generation facilities, mainly because the technology is relatively expensive and waste quantities are limited (EC, 2009).

Biomass energy accounts for 50% of Africa's total primary energy supply and about 60% in sub-Saharan Africa (Gyamfi *et al.*, 2015). Biomass resources cover about 20.8 million hectares of the 23.8 million hectare landmass of Ghana and supply about 64% of the total energy used in the country. The vast arable and degraded land mass of Ghana has the potential for the cultivation of crops and plants that can be converted into a wide range of solid and liquid biofuels.

The VRA/NED is collaborating with three entities for the development of biomass related energy projects. These include sugarcane / biogas to energy plant, a biomass (bamboo) to energy plant and a municipal waste to energy power plant.

2.6.5 Barriers to Renewable Energy Development in Ghana

According to the EC (EC, 2009), besides the fact that renewable energy technologies (RETs) are not cost competitive with other alternative energy sources in most applications, other factors have posed as important barriers to the development of RETs in the country. These barriers are:

- Absence of comprehensive RET Policies;
- Absence of regulatory framework;
- High initial cost of RETs;
- Inadequate financing schemes for RETs;
- Lack of favourable pricing policies;

- Inadequate public awareness to the benefits of RETs;

"Unless they are adequately addressed, these barriers would continue to constrain the contribution of renewable energy to national energy supply" (EC, 2009).

CHAPTER THREE

METHODOLOGY

3.0 Introduction

This chapter discusses the general and standard form of an LP Model as well as the mathematical formulation of the relevant optimization model. The cost model adopted for the purpose of this study is also discussed in detail. Projected demand cases are assumed or envisaged and each discussed under specific scenarios. Finally data used for the study are presented and the optimizer used to generate the required solutions briefly discussed.

3.1 The Linear Programming Model

Linear programming is concerned with finding an efficient way of utilizing scarce resources. It starts with the construction of a mathematical model to represent the problem. The main features of the model are: an objective to optimize and a set of constraints to satisfy. The objective and constraints are expressed as linear functions of a set of decision variables, which are under the control of the decision maker. The general form of an LP model is stated as:

Optimize $f(x) = \sum_{j=1}^{n} c_j x_i$

Subject to; $\sum_{j=1}^{n} a_{i,j} x_j \leq b_i \qquad 1 \leq i \leq p$

$$\sum_{j=1}^{n} a_{ij} x_j = b_i \qquad p+1 \leq i \leq k$$

$$\sum_{j=1}^{n} a_{ij} x_j \geq b_i \qquad k+1 \leq i \leq m$$

$$x_j \geq 0 \qquad 1 \leq i \leq n \qquad (3.1)$$

Where: $f(x)$ is an objective function and $x_j\,(1 \leq i \leq n)$ is the jth decision variable. The parameters of the model are c_j, a_{ij} and $b_i\,(i =, \ldots m, j = 1, \ldots n)$ which respectively are the ith cost coefficient, ith technological coefficient of the jth variable and the ith right hand side coefficient. The variable x_j can assume any real non-negative value.

The general form LP of (2.1) can be transformed into the standard form as:

$$\text{Optimize} \quad f(x) = \sum_{j=1}^{n} c_j x_i$$

$$\text{Subject to} \quad \sum_{j=1}^{n} a_{ij} x_j = b_i \qquad 1 \leq i \leq m$$

$$x_j \geq 0 \qquad 1 \leq i \leq n \qquad (3.2)$$

The Standard Form of LP (2.2) above is obtained by adding to or subtracting from each inequality constraint slack or surplus variables. A slack variable is a non-negative variable which when added to the Left-Hand-Side (LHS) of a less-than-or-equal-to constraint transforms it into an equality constraint. A surplus variable on the other hand transforms a greater-than-or-equal-to constraint into an equality constraint. The standard form of LP is necessary for the application of solution algorithms, since the algorithms work only with equality conditions (Lewis, 2008). The objective function may be expressed as a maximization or minimization. Objective function posed as maximization can be converted into minimization and vice versa as;

$$\text{Maximize } (c^T x) \equiv \text{Minimize } (-c^T x) \text{ and}$$

$$\text{Minimize } (c^T x) \equiv \text{Maximize } (-c^T x)$$

3.2 Mathematical formulation of the Model

In order to formulate the model, the decision variables and parameters of the problem were identified and specified. Subsequently, the objective function and constraints were formulated. These are presented as follows.

Variables:

$Supply_i$ (S_i): Optimal supply from each Energy plants.

Parameters:

$Demand_y$ (D_y): Projected electricity demand by the year y

Cap_i (C_i): Available capacities from the ith Energy plants.

$LCOE_i$: Levelized Cost of the ith plant.

$\Pr od_k$ (P_k): Current production from thermal power plants.

$\Pr od_h$ (P_h): Current production from hydro plants.

$\Pr od_s$ (P_s): Current production from solar plants.

Objective function

The objective of the problem is to minimize the overall cost of producing electricity whiles meeting the projected demands. This is given by:

$$\text{Minimize } Z = \sum_{i=1}^{n} LCOE_i . S_i \; ; \qquad (3.3)$$

$i \in \{1, 2, ..., n\}$

n the number of energy plants

Constraints:

Total supply from each Energy plant should at least meet the demand by the year *y*, where y is the target year. This is given by:

$$\sum_{i=1}^{n} S_i \geq D_y \quad (3.4)$$

Supply from each plant should at most be equal to its potential capacity. This is given by:

$$S_i \leq C_i \text{ for every } i \in \{1, 2, \ldots, n\} \quad (3.5)$$

Supply from existing thermal, hydro and solar plants (k, h, and s) should at least be equal to the current production level. This is given by:

$$S_k \geq P_k \quad (3.6)$$

$$S_h \geq P_h \quad (3.7)$$

$$S_s \geq P_s \quad (3.8)$$

Thus the resulting model is given by:

Minimize $Z = \sum_{i=1}^{n} LCOE_i . S_i$

Subject to $\sum_{i=1}^{n} S_i \geq D_y$

$$S_i \leq C_i$$

$$S_k \geq P_k$$

$$S_h \geq P_h$$

$$S_s \geq P_s$$

$$S_i \geq 0$$

3.3 The Levelized Cost of Electricity (LCOE)

The cost of electricity generated by the different sources is a calculation of the cost of generating electricity at the point of connection to a load or electricity grid. The LCOE attempts to assess different methods of electricity generation in cost terms on a comparable basis. It is an economic assessment of the cost to build and operate a power-generating asset over its lifetime divided by the total power output of the asset over that lifetime (Seth *et al.*, 2011).

It is often cited as a convenient summary measure of the overall competiveness of different generating technologies. It represents the per kilowatt-hour or megawatt-hour cost (in dollars) of building and operating a generating plant over an assumed financial life and duty cycle (EIA report, 2015). The LCOE can be thought of as the price at which energy must be sold to break even over the lifetime of the technology.

According to the Department of Energy and Climatic Change of USA, the levelized cost of a particular generation technology is the ratio of the total costs of a generic plant to the total amount of electricity expected to be generated over the plant's lifetime. Both are expressed in Net Present Value (NPV) terms. This means that future costs and outputs are discounted, when compared to costs and outputs today.

Calculating the levelized cost of energy is a fundamental principle in the energy and power industry. It basically allows the comparison of various technologies of unequal life times and capacities without resorting to developing a full-blown project finance model (Marcial, 2009).

A simplified approach is particularly appropriate when doing a rough estimate on the cost of electricity given the various technologies in a country. By applying the formula on each power plant, as if it is continuously replaced to provide incremental power to meet new incremental demand, it provides a good estimate on the cost of electricity had a new plant been constructed to replace the old plant that became obsolete (Marcial, 2009).

Key inputs to calculating LCOE includes investment/capital costs, fuel costs, fixed and variable operations and maintenance costs, discount rate, and an assumed utilization rate/capacity factor for each plant type. This type of calculation assists policy makers, researchers and others to guide discussions and decision making. The importance of the factors varies among the technologies. For technologies such as solar and wind generation that have no fuel costs and relatively small variable operations and maintenance costs, LCOE changes in rough proportion to the estimated capital cost of generation capacity (EIA report, 2015).

It is generally calculated as follows:

$$LCOE = \frac{\sum_{y=1}^{N}\left(\left(I_y + M_y + F_y\right).(1+r)^{-y}\right)}{\sum_{y=1}^{N}\left(E_y.(1+r)^{-y}\right)} \tag{3.9}$$

where

- I_y : Investment expenditures in the year y
- M_y : Operations and maintenance expenditures in the year y (fixed and variable)
- F_y : Fuel expenditures in the year y
- E_y : Electricity generation in the year y
- r : Discount rate
- N : Life of the system

LCOE of New Electricity Generating Technologies in the United State of America (USA) can be seen in Appendix C.

Due to lack of data on the investment cost of RE sources in the country, data from the International Renewable Energy Agency (IRENA) was used for the calculation of the LCOE using a standard 10% discount rate across all technologies. IRENA is an inter governmental organization that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. As of October 2012, the membership of IRENA comprised of 158 States and the European Union (IRENA, 2013).

The lack of accurate, reliable data on the cost and performance of renewable technologies is a significant barrier to their uptake. For this reason, IRENA provides in-depth and up-to-date information on the cost of generating electricity from renewables such as solar, wind power, hydropower, biomass and other sources. This information help governments, policy makers and investors to make informed decisions about the role renewables can play in the energy sector. Table 3.1 shows the IRENA estimated cost for new plants.

Table 3.1: Parameters used to calculate the LCOE

Plant Type	Plant capacity (MW)	Capacity Factor (%)	Investment Cost ($/MWh)	Operation and Maintenance Cost	Fuel Cost	Discount rate (%)	Investment Period (Yr)
Wind	300 - 500	32 - 42	83.9	9.6	0.0	10	10
Solar PV	250 - 450	22 - 27	194.6	12.1	0.0	10	10
Hydro	350 - 550	40 - 50	74.5	3.8	0.0	10	10
Biomass	150 - 300	70 - 90	55.3	13.7	42.3	10	10
Additional thermal	450 - 2000	80 - 90	14.4	1.7	57.8	10	10

Source: IRENA, 2013

In Table 3.1, the second column of the table shows the range of capacities of the considered plants, column three represent the capacity factors, column four shows the range of investment and cost of the plants (i.e. the cost of energy in dollars per 1MWh from a plant), Operations and Maintenance, and Fuel cost are represented in column five and six respectively, whiles the last two columns represents discount rate and the investment period.

In calculating the actual generation cost of a plant (e.g. wind) within the period, the cost per 1MWh of energy is multiply by the total capacity of the plant, by the total hours in a year ($24hr \times 365days = 8760hrs$), and by the investment period. That is;

1. Investment cost for a 300 MW wind plant = $83.9 \times 300 \times 8760 \times 10 =$ $2,204.89M

   Investment cost for a 500 MW wind plant will be = $83.9 \times 500 \times 8760 \times 10 =$ $3,674.82M

2. Operations and maintenance cost of wind for 300MW = $9.6 \times 300 \times 8760 \times 10 =$ $252.29M

   Operations and maintenance cost of wind for 500MW = $9.6 \times 500 \times 8760 \times 10 =$ $420.48M

3. Fuel cost for a 300MW wind plant = $0.0 \times 300 \times 8760 \times 10 =$ $0.00M

   Fuel cost for a 500MW wind plant = $0.0 \times 500 \times 8760 \times 10 =$ $0.00M

4. Total Generation Cost for 300MW-500MW wind plant is calculated as:

   Average Investment Cost + Average Operations and Maintenance Cost + Fuel Cost

$$\left(\frac{2204.89+3674.82}{2}\right)+\left(\frac{252.29+420.48}{2}\right)+0.0=\$3,276.2M$$

Similar computations were than for the remaining plants and are represented in Table 3.2.

Table 3.2: Investment and Production cost for 2014 - 2025

Plants	Cost in Million United States Dollar (USD)			
	Investment $(M)	Operations and Maintenance Cost	Fuel Cost	Total Generation cost
Wind	2,204.89 – 3674.82	252.29 – 420.48	0.0	3,276.24
Solar plant	4,261.74 – 7671.13	264.99 – 476.9	0.0	6,263.18
Hydro plant	2,284.17 – 3589.41	116.51 – 660.07	0.0	3,325.08
Biomass	726.64 – 1453.28	180.02 – 360.04	555.82 -1,111.64	2,193.72
Additional thermal	567.65 – 2522.88	67.01 – 297.84	2,278.48 – 10,126.56	7,930.21
Overall Generation cost	**23,075.67**			

Table 3.2 shows the Investment, Operations and Maintenance, and Fuel cost for the additional plants. The cost values were calculated base on the data from IRENA (See Table 3.1).

Overall Generation Cost for the 10 yrs period is $23,075.67M (i.e. sum of the Total Generation Cost of the individual plants in column five of Table 3.2).

Using the LCOE model above, simulations were run using Risk optimizer 6.3.

Many of the input parameters regarding costs of energy production are not known with certainty. By using probability distributions for these parameters and a Monte Carlo simulation that statistically selects from these distributions over and over again, a LCOE output distribution that captures the uncertainty associated with the inputs was built.

With varying capacity factors, the LCOE for the various plants were generated and the results parented in chapter four. The LCOE results would be used as parameter values for the optimization model and also for the construction of screening curves. Screening curves are a simple but powerful tool for the determination of an optimal electricity mix that satisfies a given demand (Nersesian, 2013). They are also used to determine plants that could be assigned to base load, intermediate and peak load demands. Screening curves provide a plot of cost per Megawatts hour as a function of capacity (Koomey *et al.*, 1990).

3.4 Total Generation Cost for the Existing and additional Plants

Operation and Maintenance, and Fuel cost for the existing generation plants for the year 2014 were $546.86M and $1,140.10M respectively. (GRIDCo report, 2014). If it is assumed that Operations and Maintenance, and Fuel Cost for the existing plants during the investment period of 10yrs remained the same, it implies that;

Operation and Maintenance Cost for the period would be (546.86 × 10) = $5,468.6M.

Fuel Cost during the 10yrs period would be (1140.1 × 10) = $11,401M

Total Generation Cost for the existing plants during the period would be $16,869.59M (i.e. Operations and Maintenance Cost at $5,468.6M plus Fuel Cost at $11,401M).

From Table 3.2, the Overall Generation Cost for the additional plants is $23,075.67M.

It implies that Total Generation Cost for both additional and existing plants during the investment period would be (16869.59 + 23075.67) = $39,945.26M.

Data on the capacities of the existing energy generation plants are presented in Table 3.3.

Table 3.3: Existing Hydro and Thermal plants

Generation plant	Capacity (MW)		Plant Utilisation Factor	Expected Energy (GWh)
	Installed	Dependable		
Existimg Hydro plants				
Akosombo	1,020	960	90	6,643.20
Kpong	160	140	90	1,140.55
Bui	400	380	30	998.64
Sub-Total	*1,580*	*1,480*		*8,782.39*
Existimg Thermal plants				
TAPCO (CC)	330	300	70	1,839.60
TICO (SC)	220	200	10	175.20
Sunon – Asogli (gas)	200	180	75	1,182.60
Tema Thermal Plant – TT1PP	126	110	70	674.52
Tema Thermal Plant – TT2PP	49.5	45	70	275.94
Takoradi 3 (T3)	132	120	10	105.12
Mines Reserve Plant (MRP)	80	40	75	245.28
CENIT Energy Ltd	126	110	70	674.52
Sub-Total	*1,263.5*	*1,105*		*5,172.78*
VRA Solar	2.5	2	30	5.26
Sub – Total	*2*	*2*		*17.52*
Total	**2,851.5**	**2,589**		**13,973**

Source: Volta River Authority, 2014

The capacities of the existing generation plants in Table 3.3 were used together with the parameter values in Tables 3.1, 3.2 and 3.4 to run the optimization model.

3.5 Projected Electricity Demand Cases

Three scenarios (C1, C2, and C3) are generated for three demand cases (*low demand, moderately high demand*, and *high demand* case). Scenario C1 assumes a 10% supply from renewable energy sources by 2025, whiles the remaining 90% of the total energy supply will be from remaining generation sources. Scenario C2 assumes a 20% incorporation of Renewable Energy Technologies (RETs) whiles the remaining 80% will be from the existing sources. Scenario C3 assumes a 30% incorporation of Renewable Energy Technologies (RETs) by 2025, with 70% from other generating sources.

The supply from existing energy sources (hydro, solar and thermal) is expected to increase accordingly by the projected 2025 target year. The level of increase will be determined from runs of the optimization model. Data on the potential capacities in MW of the existing plants are presented in Table 3.3.

Low demand

This demand case is based on the electricity demand level of 26,247 GWh by 2025 (See Table 3.4). It assumes relatively low economic/demographic growth and relatively high energy prices.

Moderately high demand

The Moderately high demand case is based on the electricity demand level at 36,207 GWh by 2025 (See Table 3.4). It assumes growth assumptions in between the low and high demand case scenarios.

High demand

It is based on the projected demand case of 46,165 GWh by 2025 (See Table 3.4). The high demand case assumes relatively high economic/demographic growth and relatively low energy prices.

Table 3.4 shows the projected demand by 2025. The year 2014 - 2020 projections are from the demand forecast produced by EC and VRA (See Table 2.3). The year 2021 - 2025 projections were made for the purpose of this study with an average rate of 8% per annum.

TABLE 3.4: Electricity demand projections for three scenarios from 2014 - 2025

Year	Low economic growth (GWh)	Moderately high economic growth (GWh)	High economic growth (GWh)
2014	14,828	20,200	25,620
2015	15,408	20,900	26,600
2016	16,000	21,660	27,600
2017	16,623	22,598	28,630
2018	17,280	23,613	29,948
2019	17,970	24,682	31,394
2020	18,714	25,815	32,915
2021	20024	27622	35219
2022	21426	29556	37684
2023	22925	31624	40322
2024	24530	33838	43145
2025	**26247**	**36207**	**46165**

It is evident from Table 3.4 that, base on the projections made, demand for electricity by the year 2025 in the country will be 26,247GWh, 36,207 GWh and 46,165 GWh in the low, moderately high and high demand cases respectively. The values for the three demand cases in the year 2025 were used with other parameter values from Tables 3.2, 3.3 and 4.1 to run the optimization model of which the results are presented in the next chapter.

CHAPTER FOUR

PRESENTATION AND DISCUSSIONS OF RESULTS

4.0 Introduction

In this chapter, we present and discuss the cost model in relation to the scenarios and demand cases considered in chapter three.

4.1 Results of the LCOE Model

The LCOE parameter values were obtained using Risk optimizer 6.3 by varying the capacity factor of the various energy sources considered and presented in Table 4.1.

Table 4.1: LCOE parameter values for the considered RE plants

	Wind plant	Solar plant	Hydro plant	Biomass
Capacity factor (%)	LCOE ($/MWh)	LCOE ($/MWh)	LCOE ($/MWh)	LCOE ($/MWh)
10	167.67	145.45	135.66	87.06
20	83.83	72.72	67.66	51.03
30	55.89	48.48	45.11	39.02
40	41.92	36.36	33.83	33.02
50	33.53	29.09	27.06	29.41
60	27.94	24.24	22.55	27.01
70	23.95	20.78	19.33	25.29
80	20.96	18.18	17.92	23.01
90	18.63	17.62	16.92	21.33
100	17.77	16.16	14.01	15.4

Table 4.1 shows the LCOE of Wind, Solar, Hydro and Biomass plants each with Capacity factors ranging from 10% to 100% in increments of 10%. At low Capacity factor, the Wind and solar plant in row two and three has the highest LCOE than the other plants because of their high capital cost as show in Table 3.2. Whiles at high Capacity factor, hydro has the smallest LCOE than the other plants due to its low maintenance cost.

4.2 Results of the cost model for the three demand cases

The overall optimal mix of energy supply from RE plants and the existing plants for the three demand cases under the three scenarios (C1, C2 and C3) are presented.

The output (using @RiskOptimizer version: 6.3) of the optimization model for the projected variety of demand cases are presented in Tables 4.2(a) to 4.4(c). In each Table, the first row indicates both renewable and existing plants; the second row indicates the capacities of the power plants; row three indicates the capacity factors of the power plants; row four indicates the power output (in MW) from each of the power plants to meet the projected electricity demand; Row five indicates the optimal cost of generating power from the plants.

4.2.1 The Low Demand Case.

The capacity of the RE that should be incorporated in the energy mix is 1204MW (Wind 400MW, Solar 300MW, Hydro 350MW and Biomass 200MW). Output from the various plants to meet the projected demand of 26247GWh in the low demand case scenario is shown in Table 4.2(a).

Table 4.2(a): Scenario C1. Output for 10% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	450	2859
Capacity factor (%)	25	35	35	40	51	90
Output (MW)	100	70	80	50	108	2589
Optimal Cost ($M)	**15,748.2**					

From Table 4.2(a), the total capacity of both additional and existing plants to be installed is 4559MW. For the projected demand of 26247GWh in the low demand case scenario to be met with 10% share from RE, output from Wind, Solar, Hydro, Biomass, Additional thermal and Existing plants should be 100MW, 70MW, 80MW, 50MW, 108MW and 2589MW respectively. This means that the Wind plant when installed will be utilized at a Capacity factor of 45%, both solar and Hydro plant at 35%, and the existing plants 90%. This combination will result in an optimal cost of $15,748.2M to meet demand at 26247GWh.

Output from the existing plants, with 599MW (i.e. 20% of the projected demand of 2996MW) from RE that is required to meet the projected demand of 26247GWh in the low demand case scenario is shown in Table 4.2(b).

Table 4.2(b): Scenario C2. Output for 20% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	450	2859
Capacity factor (%)	45	58	40	52	0	85
Output (MW)	180	175	140	104	0	2397
Optimal Cost ($M)	**15,000.4**					

As shown in the Table 4.2(b), for the projected demand of 26247GWh in the low demand case scenario to be met with 20% share from RE, capacity output from Wind, Solar, Hydro, Biomass, and Existing plants should be 180MW, 175MW, 140MW, 104MW, and 2397MW with Capacity factors of 45%, 58%, 40%, 52%, and 85% respectively. The zero (0) output from additional thermal indicates that the projected demand of 26247GWh will be met with the incorporation of 20% RE to the existing plants.

Table 4.2(c) shows the output from the existing plants, with 899MW (i.e. 30% of the projected demand of 2996MW) from RE that is required to meet the projected demand of 26247GWh in the low demand case scenario.

Table 4.2(c): Scenario C3. Output for 30% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	450	2859
Capacity factor (%)	57	97	66	75	0	81
Output (MW)	229	290	230	150	0	2097
Optimal Cost ($M)	**14,776.9**					

As shown in Table 4.2 (c), for the projected demand to be met with 30% share from RE, capacity output from Wind, Solar, Hydro, Biomass, and Existing plants should be 229MW, 290MW, 230MW, 150MW, and 2097MW with Capacity factors of 57%, 97%, 66%, 75%, and 81% respectively. The zero (0) output from additional thermal indicates that the projected demand of 26247GWh will be met with the incorporation of 30% RE to the existing plants. The optimal cost of meeting the projected demand of 26247GWh with 30% share from RE is $14,776.9M which is less than the cost when 10% or 20% of RE is incorporated. This is an indication that when more RE sources are incorporated in the countries energy mix, the cost of energy generation could be reduced. Similar interpretations follow for the outputs of the other scenarios and demand cases displayed in the Tables 4.3(a) to 4.4(c).

4.2.2 The moderately high demand Case

Table 4.3(a) shows the output from the existing plants, with 413MW (i.e. 10% of the projected demand of 4133MW) from RE that is required to meet the demand of 36207GWh in the moderately high demand case scenario.

Table 4.3(a): Scenario C1. Output for 10% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	1500	2859
Capacity factor (%)	30	34	29	45	75	90
Output (MW)	120	103	100	90	1131	2589
Optimal Cost ($M)	**30,525.1**					

Output from existing plants, with 827MW (i.e. 20% of the projected demand of 4133MW) from RE that is required to meet the demand of 36207GWh in the moderately high demand case scenario is shown in Table 4.3(b).

Table 4.3(b): Scenario C2. Output for 20% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	1500	2859
Capacity factor (%)	60	69	57	90	71	90
Output (MW)	240	207	200	180	717	2589
Optimal Cost ($M)	**25,085.3**					

Table 4.3(c) shows the output from the existing and new plants, with 1240MW (i.e. 30% of the projected demand of 4133MW) from RE that is required to meet the demand in the moderately high demand case scenario.

Table 4.3(c): Scenario C3. Output for 30% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	500	450	550	370	1500	2859
Capacity factor (%)	78	67	64	54	65	90
Output (MW)	390	300	350	200	304	2589
Optimal Cost ($M)	**23,118.6**					

4.2.3 The High Demand Case

For 10% share of RE that is required to meet the projected demand of 46165GWh in the High demand case scenario, the results are shown in Table 4.4(a).

Output from existing and additional plants, with 827MW (i.e. 10% of the projected demand of 5270MW) from RE that is required to meet the demand in the high demand case scenario is shown in Table 4.4(a).

Table 4.4(a): Scenario C1. Output for 10% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	2000	2859
Capacity factor (%)	53	49	29	35	90	90
Output (MW)	210	147	100	70	1892	2589

Optimal Cost ($M)	**38,922.6**

Output from the existing and additional plants, with 1054MW (i.e. 20% of the projected demand of 5270MW) from RE that is required to meet the demand of 46165GWh in the high demand case scenario is shown in Table 4.4(b).

Table 4.4(b): Scenario C2. Output for 20% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	400	300	350	200	1500	2859
Capacity factor (%)	60	69	57	90	93	90
Output (MW)	240	207	200	180	1300	2589
Optimal Cost ($M)	**33,205.3**					

Table 4.4(c) shows the output from the existing and additional plants, with 1581MW (i.e. 30% of the projected demand of 5270MW) from RE that is required to meet the demand in the high demand case scenario.

Table 4.4(c): Scenario C3. Output for 30% share of RE

Plant	Wind	Solar	Hydro	Biomass	Additional Thermal	Existing Plants
Capacity(MW)	500	450	550	370	2000	2859
Capacity factor (%)	86	82	87	81	55	90
Output (MW)	430	370	480	300	1101	2589
Optimal Cost ($M)	**29,478.6**					

4.3 Pictorial representation of results

Pictorial representation of the output from the RE plants are shown in Figures 4.1 to Figure 4.3

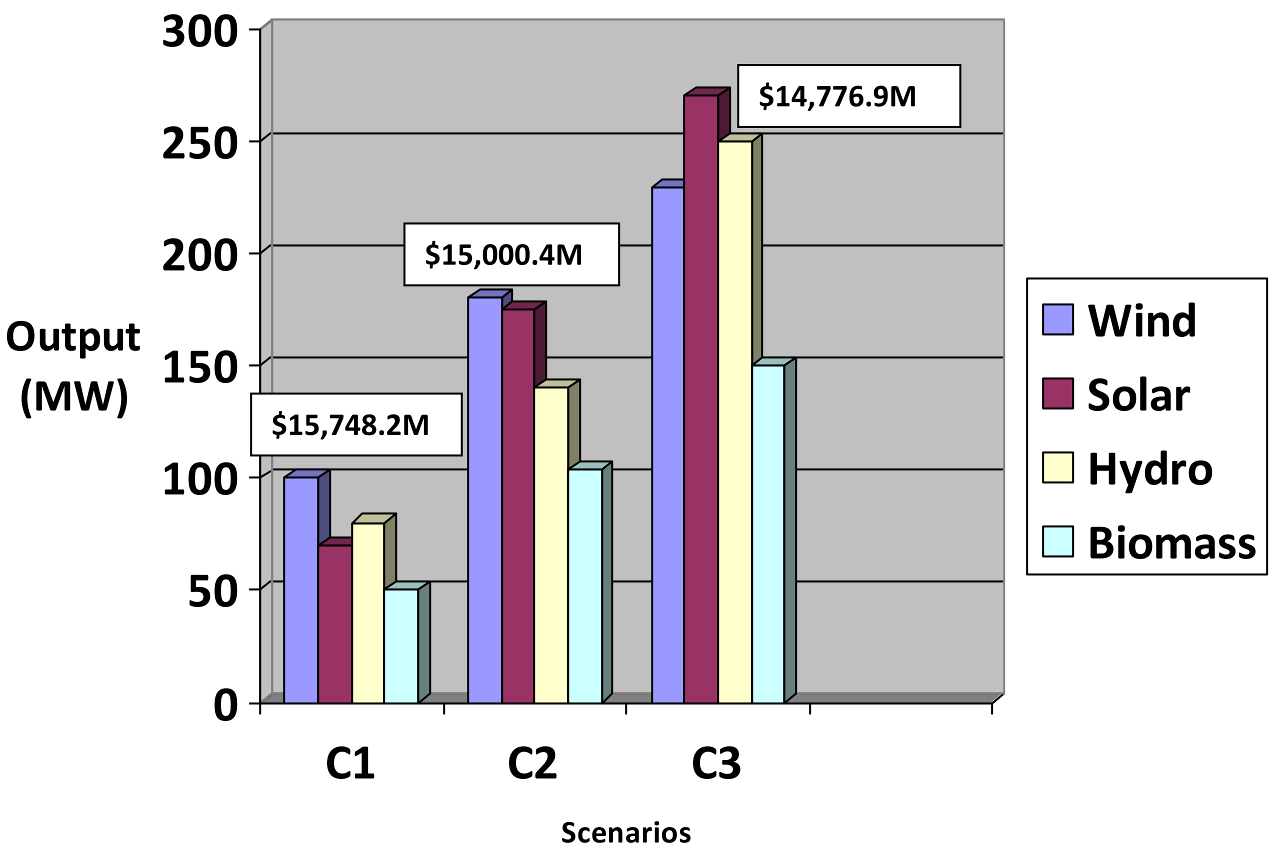


Figure 4.1: Output (MW) and Cost ($M) of RE in low demand case

It is evident from Figure 4.1 that for 10% share of RE in Ghana's generation mix, greater output would be from wind, followed by hydro, solar and biomass with an optimal cost $15,748.2M. For 20% share, wind and solar would contribute more to meet incremental demand with a cost of

$15,000.4M, whiles for 30% share, solar and hydro would contribute more at an optimal cost of $14,776.9M to meet the demand of energy. Similar interpretation applies to Figures 4.2 and 4.3.

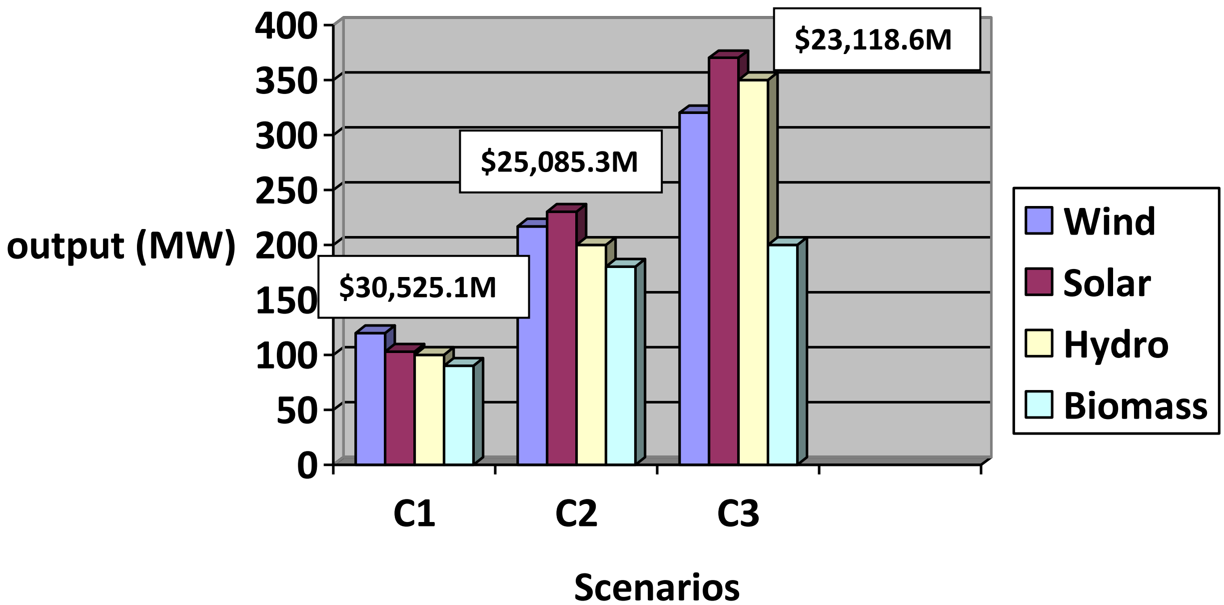


Figure 4.2: Output (MW) and Cost ($M) of RE in moderately high demand case

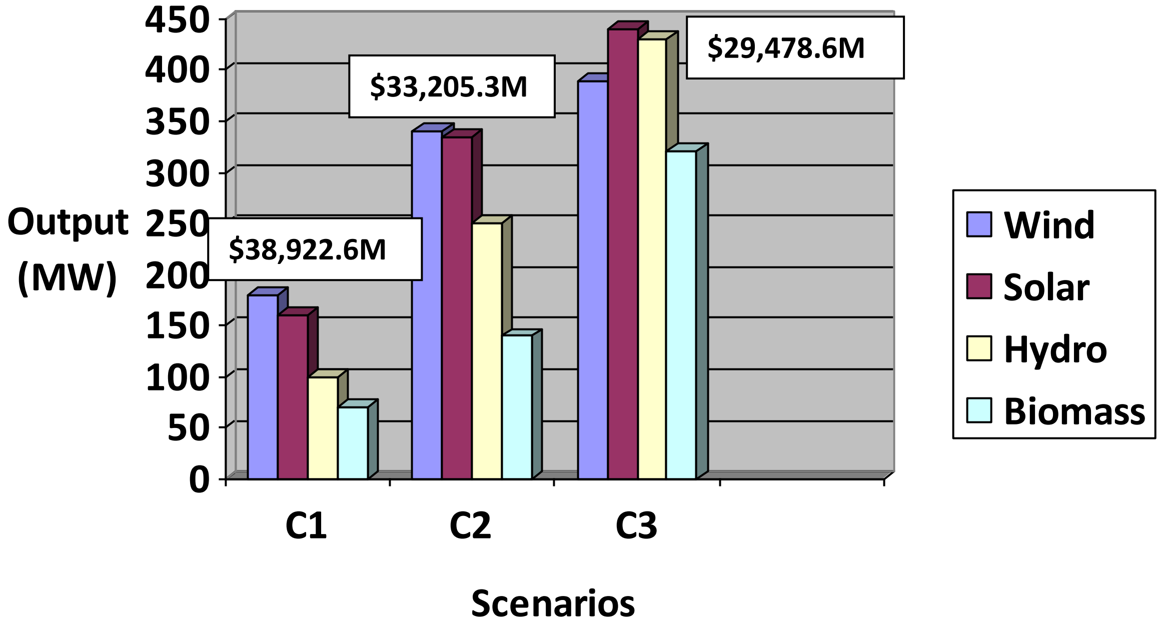


Figure 4.3: Output (MW) and Cost ($M) of RE in high demand case

4.4 Summary of results

Table 4.5: Optimal output of the plants under the three demand cases and scenarios

Plants	Low Demand (MW)			Moderately high demand (MW)			High Demand (MW)		
	Scenarios			Scenarios			Scenarios		
	C1	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**
Wind	100	180	229	413	240	390	210	410	430
Solar	70	175	290	120	207	300	147	294	370
Hydro	80	140	230	103	200	350	100	210	480
Biomass	50	104	150	100	180	200	70	140	300
Additional thermal	108	0	0	869	455	304	1892	1365	838
Existing plants	2589	2397	2097	2851	2851	2589	2851	2851	2851
Total	**2996**			**4133**			**5270**		

The summarized results in Table 4.5 indicates that to meet the projected demand of 2996MW of power in the low demand case under the three scenarios, the wind power plant would contribute 100MW, 180MW, and 229MW under C1, C2 and C3 respectively. The solar plant should contribute 70MW, 175MW and 290MW under C1, C2 and C3 respectively. The hydro plant should contribute 80MW, 140MW and 230MW under C1, C2 and C3 respectively. The same interpretation applies to the remaining plants under the low demand case, and to the plants in the other demand cases.

Table 4.6: Optimal Cost of power generation under the three demand cases and scenarios

	Optimal Cost ($M)		
	Scenarios		
Demand Cases	C1 (10%)	C2 (20%)	C3 (30%)
Low	15,748.2	15,000.4	14,776.9
Mid	30,525.1	25,085.3	23,118.6
High	38,922.6	33,205.3	29,478.6

From Table 4.6, the optimal costs of producing power to meet the projected energy demands in the low demand case under C1, C2 and C3 are $15,748.2M, $15,000.4M and $14,776.9M respectively. The optimal costs of producing power under the moderately high demand case are $30,525.1M in C1, $25,085.3M in C2 and $23,118.6M in C3. The optimal costs in the high demand case are $38,922.6M in C1, $33,205.3M in C2 and $29,478.6M in C3. It can be observed from Table 4.6, the cost decreases from scenario C1 to C3 in all the three demand cases.

Comparing these results from the cost model to the Total Generation Cost of $39,945.26M (See section 3.3), it can be seen that with 10%, 20%, and 30% incorporation of RE in the low demand case, the total investment cost would be reduced by $24,197.06M in C1, $24,944.86M in C2 and $25,168.36M in C3 respectively. Similar trend is observed in the other demand cases.

This is an indication that when more of RE is incorporated in our current generation mix, the cost of producing power to meet incremental demand in the country could be substantially reduced.

4.5 Screening Curves

Table 4.1 was used to construct screening curves for the various plants to determine plants that could be assigned to base load, intermediate and peak load plants. Base load plants are the plants that operate almost continuously to meet the minimum level of power demand, generally at annual utilization rates of 70 percent or higher. The main advantages of the base load power plants are cost efficiency and reliability at the optimal power levels. Above-base power demand (above the base) is handled by intermediate and peak power plants, which are also included to the grid.

Intermediate load plants are facilities that operate less frequently than base load plants, generally at annual utilization rates between 25 and 70 percent. Peaking power plants are power plants that generally run only when there is a high demand known as peak demand for electricity, generally at annual utilization rates less than 25 percent. Because they supply power only occasionally, the power supplied commands a much higher price per megawatt hour than base load power (EIA, 2013).

Screening curves show the respective LCOE for each of the plants (Wind, Solar, Hydro and Biomass) at different Capacity factors. The screening curves for the considered plants are obtained by plotting Capacity factors against cost. The screening curves for the four RE plants are shown in Figure 4.4.

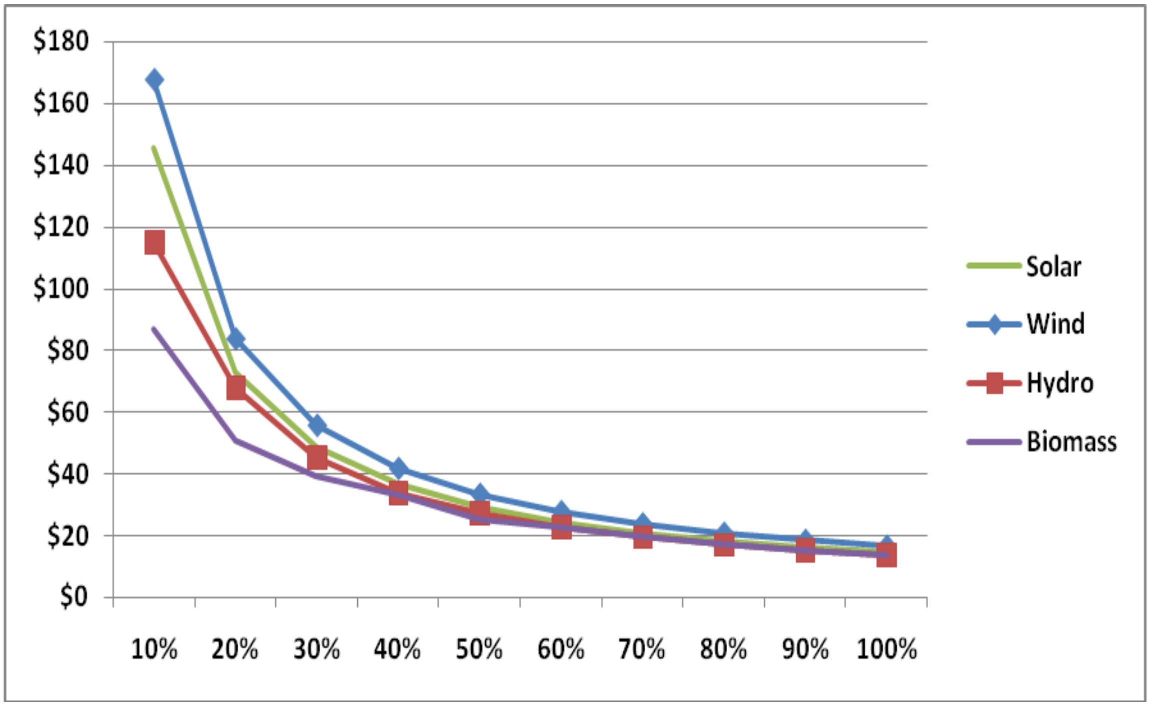


Figure 4.4: Screening curve for the four RE plants

It is very much evident from the above Figure 4.4 of Screening Curves that at low Capacity factors, the Wind and solar plants has the highest LCOE than the other plants which could be as a result of their high capital cost as indicated in Table 3.1. Whiles at high Capacity factors, hydro and biomass has the lowest LCOE.

Because of the high capital cost of wind and solar, and also the fact that they are intermittent energy sources whose output depends on weather conditions, they cannot be relied upon to meet constant electricity supply needs, nor can they be immediately employed to respond to peak demands. Wind and solar could therefore be efficient and most suitable when used as intermediate load plants. Hydro and biomass could however be used to support base load plants since their power supply at high capacity factors could result in lower cost than the other plants. The combination of wind and solar as intermediate load plants with hydro and biomass as base load plants could meet the demand for energy in the country at minimum cost of generation.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.0 Summary

This study has been the application of the Levelized Cost of Energy (LCOE) model situated within a linear programming frame to work an energy mix problem conceived for Ghana. The main objective was to find a minimum cost of investment in RE sources, such as Hydro, Wind, Solar and Biomass that will meet projected expected demand levels in specific time periods in the future and that ensured a modest (10%), (20%) or even (30%) incorporation of these renewables. This section concludes the discussions and makes recommendation aimed at making the findings of practical value to the country.

5.1 Conclusions

The optimal energy mix investment problem for Ghana was formulated as Linear Programming and the resulting model tested using secondary data from VRA websites and other relevant sources. The test results showed that the growing demand of energy in the country could be met at a minimum cost with the incorporation of RE into the existing mix. Comparing the Total Investment Cost of $39,945.26M and the optimal cost from the cost model results, there was significant reduction in the cost of investment. This was evident in all the three demand cases and scenarios.

In the low demand case, the incorporation of 10% RE yielded an optimal cost of $15,748.2M representing about 60% reduction of the overall investment cost. With 20% incorporation of RE, total investment cost reduced by $24,945M. The total investment cost further reduced by $25,168.36M with 30% incorporation of RE.

The optimal cost of producing power to meet the projected energy demand in the moderately high demand case under C1, C2 and C3 were $30,525.1M, $25,085.3M and $23,118.6M respectively. This showed a reduction in the total generation cost by 23.6% in C1, 37.2% in C2 and 42.12% in C3.

Optimal cost in the high demand case was $38,922.6M in C1 (representing 2.6% reduction of total generation cost), $33,205.3M in C2 (representing 16.9% reduction of total generation cost) and $29,478.6M in C3 (representing 26.2% reduction of total generation cost). This is an indication that when more of RE sources are incorporated into Ghana's current generation mix, the cost of producing power to meet incremental demand in the country could be substantially reduced.

Screening curves were also used in analyzing the results of the LCOE model in other to determine the plants that should be used as either base load, intermediate load or peak load in meeting the incremental demand. From the results, it was found out that wind and solar could be used as intermediate load plants due to their high capital cost, while hydro and biomass used to support base load plants since their power supply at high capacity factors could result in lower cost than the other plants. These combination of wind and solar as intermediate with hydro and biomass as base load plants could meet the demand for energy in the country at minimum cost of generation.

The result from the study depicts that the cost of generation energy from thermal are significantly higher as compared to the cost of RE generation. The total generation cost declines as more RE source were incorporated but rises as more thermal were incorporated. The main reason for the high thermal generation cost is due to their fuel cost (See Table 3.3). For RE plants, the production cost is extremely low due to little or absence of any fuel requirements (See Table 3.3). For this reason, emphasis on the development of RE generation would be a prudent strategy in order to keep the generation cost low and to meet incremental demand for energy in the country.

5.2 Recommendations

Based on the findings of the study, the following recommendations are made:

1. It is evident that there is very little or no data on the research area, hence information that has been made available through the internet amongst others do not reflect exactly the reality on the ground. It is therefore recommended that data on the research area such as cost of energy production from each of the existing plants should be made available to the public for further research on the subject area to be carried out.
2. Considering the reduction of generation cost that goes with RE incorporation in the energy mix, it is recommended that the government should placed emphasis on the development of RE generation in order to keep the generation cost low and to meet incremental demand for energy in the country.
3. Review of related works revealed that the cost of RE equipments could decrease in future. Based on this, it is recommended that further research should be focused on confirming these results by taking also into account possible variations of cost of RE plants.
4. Further research could also be conducted to include other different power technologies such as Coal, Nuclear, and Geothermal.

REFERENCES

Antonio, J., Akwensivie, F., Edwin, I. A., Brew-Hammond, A. and. Akuffo, F. O. (2003). Wind Energy Resource Assessment in Ghana. Paper presented by F. K. Appiah (on behalf of authors), World Wind Energy Conference, Cape Town, South Africa.

Akuffo, F.O (2007). Role of Renewable. Brew-Hammond, A. A. & Kemasuor, F (Eds). *Energy Crisis in Ghana. Drought, Technology or Policy?* (Pp45-52). Kumasi. KNUST Publishing Studies.

Alternative Energy Africa (2009). Ghana Receives Smart Grid from BPL Global. Available at *www. AE-Africa.com*. (Accessed on 02/12/2013)

Bazaraa, M.S., Jarvis, J.J. and Sherali, H.D. (2005). Linear Programming and Network Flows, 3rd ed., Wiley Publications.

Bonacina, F. (2013). The optimal generation mix for an electricity producer: the case of Italy. *https://boa.unimib.it/retrieve/handle/10281/49725/73876/phd_unimib_056283.pdf.* (Accessed on 23/5/2014)

Christian, E.J. (2014). modeling hydro – thermal power generation scheduling using Mixed Integer Linear Programme. Thesis submitted to the University for Development Studies. Navrongo campus, Ghana.

Dilip, A. and Marika, T. (2009). Sustainable energy for developing countries. *https://sapiens.revues.org/823*. (Accessed on 2/3/ 2014).

Energy Commission (2006). Strategic National Energy Plan 2006-2020. Energy Supply to the Economy. Annex I of IV. Electricity. *http://www.energycom.gov.gh/files/snep/MAIN%20REPORT%20final%20PD.pdf.*

(Accessed on 14/10/2014).

Energy Commission (2009). Renewable Energy Policy Framework for Climate Change Mitigation in Ghana. *www.ecowrex.org/system/files/repository/2009_re-policy-framework-for-climate-change_reeep-energy-commission_.pdf. (Accessed on 14/10/2014).*

Energy Commission (2012). Supply and Demand Outlook for Ghana. *https://s3.amazonaws.com/ndpc-static/pubication/2012+Energy+Outlook+for+Ghana.pdf.* (Accessed on 14/10/2014)

Energy Commission (2014). Supply and Demand Outlook for Ghana. *https://s3.amazonaws.com/ndpc-static/pubication/2014+Energy+Outlook+for+Ghana.pdf.* (Accessed on 14/10/2014)

Energy Information Administration, Annual Energy Outlook (2015), U.S. Levelized Cost of New Electricity Generating Technologies. *http://www.eia.gov/forecasts/aeo/pdf/0383%282015%29.pdf.* (Accessed on 3/06/2014)

Essah, E. A. (2011). Energy generation and consumption in Ghana. *West Africa Built Environment Research (WABER).* pp. 391-401.

Fernando, S. (2011). Quantifying the Combined Impact of Wind and Solar Power Penetration on the Optimal Generation Mix and Thermal Power Plant Cycling. *http://web.mit.edu/ferds/www/De_Sisternes_2011_YEEES_v3.pdf.* (Accessed on 23/1/2015).

Ghana Grid Company Limited, (2014). Electricity supply plan. *http://www.gridcogh.com/media/photos/forms/supplyplan/2014_Electricity_Supply_Plan.pdf.*

(Accessed on 3/06/2014)

Gyamfi, S., Mawufemo, M., Sinisa, D. (2015). Improving electricity supply security in Ghana. The potential of renewable energy. *Journal of Renewable and Sustainable Energy Reviews.* 43(2015)1035–1045

Henry, M. K. C., Yunhe, H. and Felix, F. W. (2010). Wind Power Investment in Thermal System and Emissions Reduction. The IEEE Power and Energy Society (PES).

Iddrisu, M. (2014). The Best Mix Of Power Sources: The Best Strategy To Ending The Electricity Crisis In Ghana. *http://allafrica.com/stories/201403120940.html.* (Accessed on 11/4/2014)

International Energy Agency (2013). World energy outlook. Paris. *https://www.iea.org/Textbase/npsum/WEO2013SUM.pdf.* (Accessed on 12/01/1015)

IRENA (2013), West African power pool. Planning and prospects for renewable energy. *https://www.irena.org/DocumentDownloads/Publications/WAPP.pdf.* (Accessed on 12/01/1015)

Koomey, J., Arthur, H. R., Ashok, G.,(1990). Conservation screening curves to compare efficiency investments to power plants, Energy Policy, Volume 18, Issue 8.

Konno, H. & Yamazaki, H. (1991). Mean-Absolute Deviation Portfolio, Optimization Model and its Applications to Tokyo Stock Market, Management Science, Vol.37, pp 519-531.

Lewis, C. (2008). Linear Programming, Theory and Applications. https://www.whitman.edu/Documents/Academics/Mathematics/lewis.pdf. (Accessed on 17/3/14)

Marcial T. O, (2009). How to calculate the Levelized Cost of Energy – a simplified approach. *http://www.appropedia.org/Levelised_Cost_of_Electricity_Literature_Review*. (Accessed on 24/12/2014)

Martin, T., Diesendorf, H. (2009). Optimal thermal mix in electricity grids containing wind power. *Journal of theoretical and applied information technology*. vol. 48 no.1

Attachie, J.C. and Amuzuvi, C.K. (2013). Renewable Energy Technologies in Ghana: Opportunities and Threats. Research Journal of Applied Sciences. 6(5): 776-782

Muhammad, F. S., Muhammad, L, Naveed, A., Hassan, H., Qureshi, I.M., Ihsan, H., and Yasin, C, (2012). Optimization Model using WASP-IV for Pakistan's Power Plants Generation Expansion Plan. Faculty of Electronics Engineering/International Islamic University, Islamabad, Pakistan.

Ministry of Energy, (2010). Energy sector strategy and development plan. *http://ghanaoilwatch.org/images/laws/energy_strategy.pdf*. (Accessed on 2/7/2014)

Murtagh, B.A. and Saunders, M.A. (1978). Large-Scale Linearly Constrained Optimization, Mathematical Programming Vol. 14, pp41- 72.

Nersesian, R. (2013). *Energy Risk Modeling*. Revised First Edition. Palisade Corporation. 798 Cascadilla Street Ithaca, NY USA.

Reinhard, M., Barbara, G., and Günther, W., (2010). Optimization of E.ON's Power Generation with a Special Focus on Renewables. E.ON Energy Research Center Series. Volume 2, Issue 2.

Saeko, S., Ryoichi, K. and Yasumasa, F. (2010). Evaluation of the Optimal Power Generation Mix with Regional Power Interchange considering Output Fluctuation of Photovoltaic

System and Wind Power Generation. *http://eneken.ieej.or.jp/3rd_IAEE_Asia/pdf/paper/021p.pdf*. (Accessed on 24/03/2014)

Seth, B.D., Fengqi, Y., Thomas, V. and Alfonso, V. (2011). Assumptions and the levelized cost of energy for photovoltaics. Journal of Energy & Environmental Science. (http://pubs.rsc.org | doi:10.1039/C0EE00698J)

Taha H.A, (2011). Operations Research: An Introduction 9th Ed. Pearson Edu. Inc., Prentice Hall, USA, 2011.

Theo, A. and Festus, A. (2014). Pricing and deregulation of the energy sector in Ghana: Challenges & Prospects. Ghana Energy Situation Report Q1. *http://www.academia.edu/4372434/pricing_and_deregulation_of_the_energy in_ghana.* (Accessed on 10/09/2014)

Umar, B. (2010). Financial Assessment of the Investment Potential of Renewable Energy Electricity Production in Ghana. *http://www.smcuniversity.com/working_papers/dissertation_abstracts/Umar_Bawah.pdf*. (Accessed on 23/5/2014)

Vahakn, K., and Leila, S. (2014). Optimal Renewable Energy Mix of the power sector by 2020; Investment Cost Implications for Lebanon. *http://climatechange.moe.gov.lb/viewfile.aspx%3Fid%3D214*. (Accessed on 11/3/2015)

Volta River Authority, (2015). Ghana's power outlook – Facts and Figures. *http://www.vra.com/resources/others/power_outlook_may_2014.pdf* . (Accessed on 14/6/2014)

Volta River Authority, (2015). Profile of VRA. *http://www.vra.com/about_us/profile.php*. (Accessed on 14/6/2015).

World Bank, (2009). Ghana accelerating growth to halve poverty. *http://www.worldbank.org/ida*. (Accessed on 11/02/2015)

Zhou, J. (2010). 20% Wind Generation and the Energy Markets. A Model and Simulation of the Effect of Wind on the Optimal Energy Portfolio. *http://castlelab.princeton.edu/theses/Zhou,%20Jessica-senior%20thesis%20final%20April%202010.pdf*. (Accessed on 15/6/2014)

APPENDICES

Appendix A: Investment and Production Cost Plants

Plants	Investment and Production cost (Million USD)				
	Investment	OPERATIONS AND MAINTENANCE	Fuel	TOTAL	Average total cost
Wind	2204.89 – 3674.82	252.29 – 420.48	0.0	2457.18 - 4095.3	3276.24
Solar plant	4261.74 – 7671.13	264.99 – 476.9	0.0	4378.25 - 8148.11	6263.18
Hydro plant	2284.17 – 3589.41	116.51 – 660.07	0.0	2400.68 4249.48	3325.08
Biomass	726.64 – 1453.28	180.02 – 360.04	555.82 -1111.64	1462.48 - 2924.96	2193.72
Additional thermal	567.65 – 2522.88	67.01 – 297.84	2278.48 – 10126.56	2913.14 12947.28	7930.21
Total	10045.09 - 18937.52	880.82 - 2215.41	2834.3 - 11238.2	13760.21 32391.13	13760.21 32391.13
Average total cost	14491.31	1548.12	7036.25	27249.46	**23075.67**

Appendix B: LCOE of New Electricity Generating Technologies in the United State of America (USA).

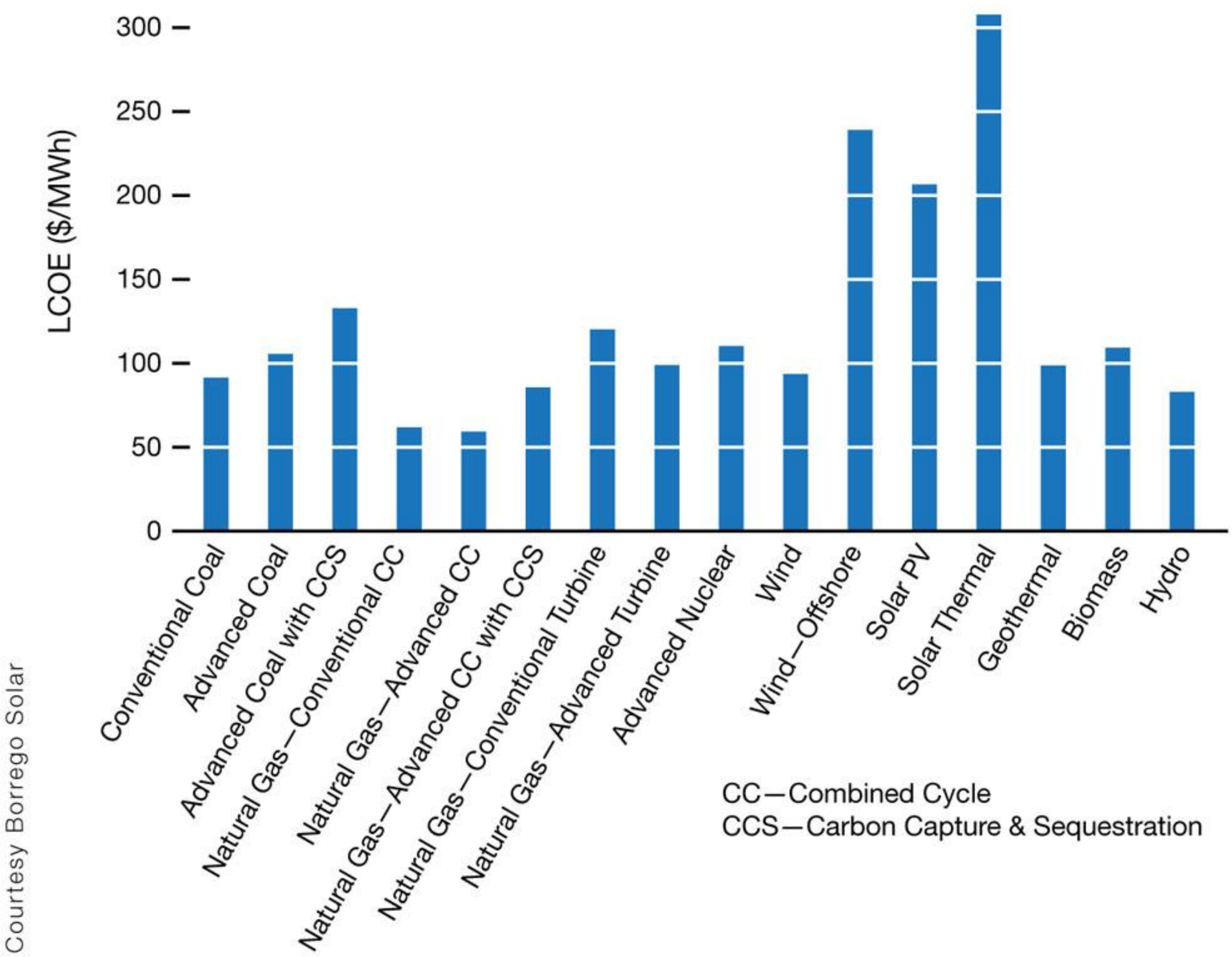
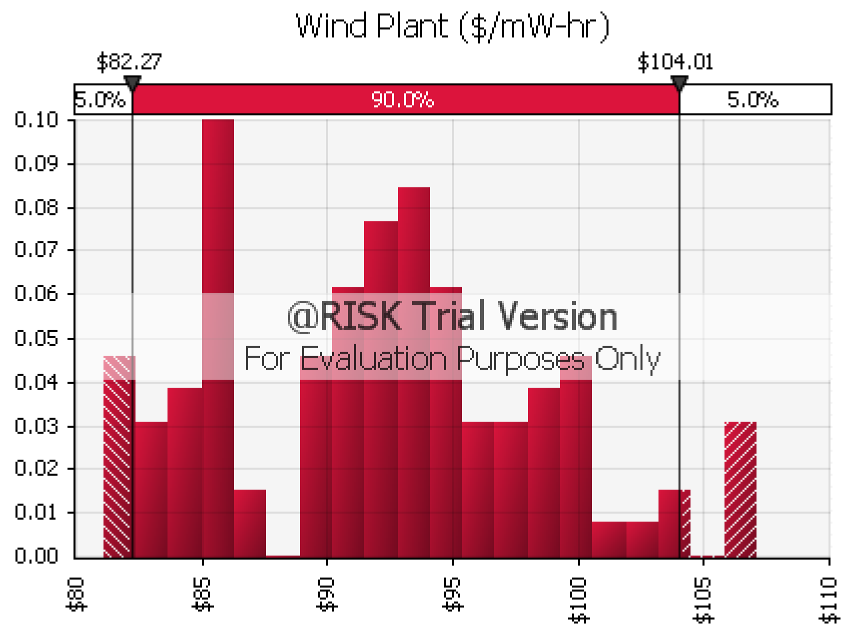


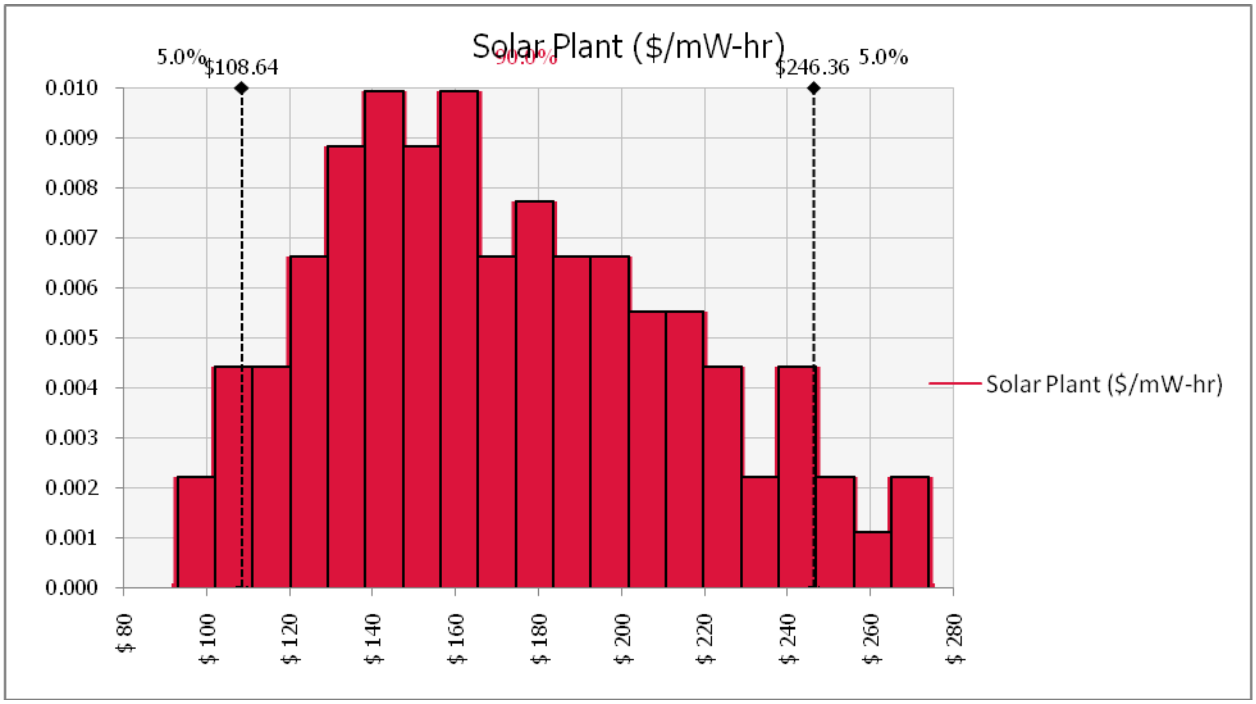
Figure 1 This chart summarizes the average LCOE by technology for power plants entering service in 2016 in the US, as estimated by the Energy Information Administration.

Appendix C: Simulated Graph of Wind Plant

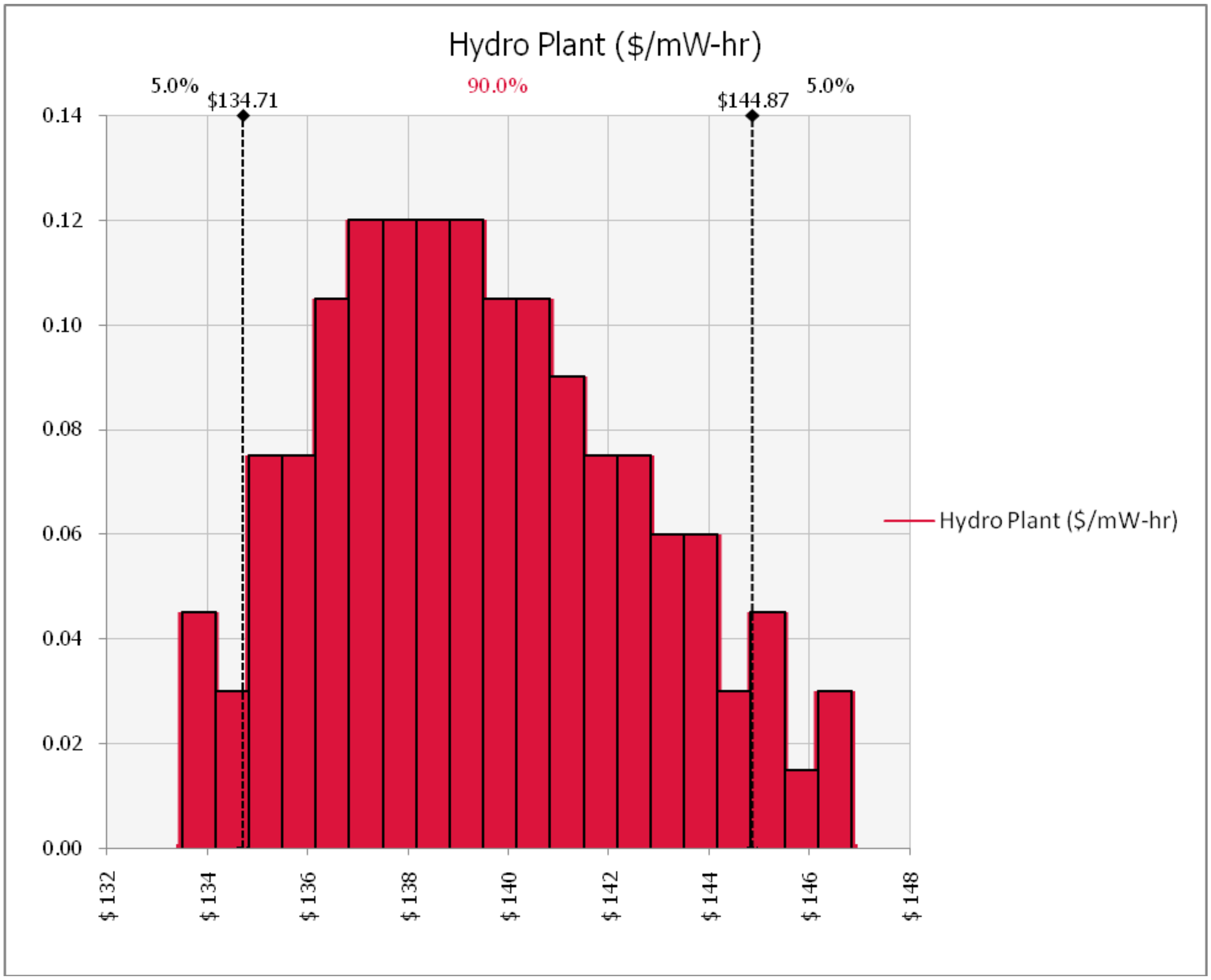


Statistics	Wind Plant ($/mW-hr)
Cell	Wind plant!C49
Minimum	$81.084
Maximum	$107.133
Mean	$92.163
Mode	$85.540
Median	$92.231
Std Dev	$6.391
Skewness	0.3067
Kurtosis	2.6129
Values	100
Errors	0
Filtered	0
Left X	$82.27
Left P	5.0%
Right X	$104.01
Right P	95.0%
Dif. X	$21.740

Appendix D: Simulated Graph of Solar Plant



Appendix E: Simulated Graph of hydro Plant



Hydro Plant ($/mW-hr)
5.0%
$134.71
90.0%
$144.87
5.0%
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$ 132
$ 134
$ 136
$ 138
$ 140
$ 142
$ 144
$ 146
$ 148
Hydro Plant ($/mW-hr)