Addis Ababa University

Addis Ababa Institute of Technology

Department of Electrical and Computer Engineering

OPTIMAL POWER GENERATION EXPANSION PLANNING FOR ETHIOPIAN ELECTRIC POWER SYSTEM

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By

Girmaw Teshager

Advisor: Prof. Wolde-Ghiorgis Woldemariam

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APPROVED BY BOARD OF EXAMINERS

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Chairman, Department of Graduate Committee	Signature
Prof. Wolde-Ghiorgis Woldemariam	____________
Advisor	Signature
______________________________	____________
Internal Examiner	Signature
______________________________	____________
External Examiner	Signature

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ABBREVIATIONS

GDP	: Gross Domestic Product
EEPCo	: Ethiopian Electric Power Corporation
U.S EIA	: United States Energy Information Administration
CDM	: Clean Development Mechanism
REDD	: Reducing Emissions from Deforestation and Forest Degradation
IEA	: International Energy Agency
USD	: United States Dollar
LPG	: Liquid Petroleum Gas
ECSA	: Ethiopian Central Statistical Authority
LV	: Low Voltage
HV	: High Voltage
GTP	: Growth and Transformation Plan
ICS	: Interconnected System
UNFCCC	: United Nations Frame Convention on Climate Change
LP	: Linear Programming
ISO	: International Organization for Standardizations

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ABSTRACT

This thesis presents an optimal power generation expansion planning model that considers the growth of fuel prices and its fluctuation, power risks, benefits of carbon-trading in generation expansion decision. The developed model is applied to Ethiopian Electric Power System for ten years in the future.

In Ethiopian electric power system, the electric demand has been running ahead of supply. In addition, the growth of fuel price can affect the country economy. Moreover, since the dominant energy consumption is covered by firewood and charcoal (both take a share of 78% of national energy balance), the environmental degradation and deforestation is being continually increased.

Therefore, to minimize these problems, a multi-objective model preceded by electric demand forecasting is developed. Attributes, which are considered in the work, include investment and generation cost of the power generating units, the environmental impacts, the amount of imported fuels and carbon-trading benefit.

The model is simulated by written code in MATLAB work space. The MATLAB code simulates the model to outcome the generation of each power plant at minimized cost incurred for building the power plants, production of electric energy and fuel to be imported.

The forecasted demand shows that the average demand annual growth rate is 34.78% by scenario-1 and 31.98% by scenario-2. EEPCo plan is annually deviated from the forecasted values by an average of 32% and 27% with respect to scenario-1 and scenario-2 respectively.

The investment and generation cost expended is an average of 0.0112 USD to produce a kWh electric energy for extra power generation in case of carbon trade consideration in generation expansion planning. It is very low compared to the cost of an average of 0.111 USD to produce a kWh electric energy by regular approach like model-2. Oil fuel for power plants and cooking in urban areas comes to nil in the proposed planning periods.

Keywords: Power Generation, Optimization, Planning, Carbon-Trade, Linear Model, Forecasting.

CHAPTER ONE

INTRODUCTION

1.1. Background

There are no reasons to doubt that in the future our existence will be more and more dependent upon the energy. To satisfy their energy requirement, the people attention tends to electrical energy. Electrical energy is considered as superior to all other forms due to cheapness, convenient and efficient transformation, easy to control, cleanness, greater flexibility and versatile form. It finds innumerable uses in home, industry, agriculture, transport, defense, aviation, public center, etc. Electrical energy is not only for doing desired activities but also to improve quality of life of the people [15].

Electricity is a critical economic infrastructure. If not delivered where and when needed serious damage ensures for the economy. One study estimates that the output lost, due to a one-day power cut, is to be between 10% to 15% of that day's GDP[1]. Considerable potential output has been lost due to power cuts in the past few years in Ethiopia. Potential losses from power disruption will increase in the future as the economy grows and the relative contributions of the industry and service sectors increase in the economy [1, 2].

Electricity is so basic to the world economy that certain electricity indices are used to express a country's economic standing (consumption or production of electricity per capita) and the standard of living enjoyed by a people (per capita electricity consumption in the domestic sector) [9]. On this base, Ethiopian production of electricity per capita from 2004/05 to 2008/09 is 37 kWh, 42 kWh, 44 kWh, 45 kWh, and 48 kWh. Per capita electricity consumption per month in the domestic sector in the same years is also 74 kWh, 68 kWh, 73 kWh, 60 kWh and 62 kWh (Calculated from the 2008/2009 report of EEPCo Facts in Brief). These values tell that Ethiopia is listed at the bottom of the world countries in the status of electricity production (chart 1 and 2).

[1] *Sourced from Diversity and security for the Ethiopian Power System, Ethio Resource Group (ERG) for HeinrichBoll Foundation (HBF) and Forum for Environment (FfE), August 2009, To be Published*

Chart 1: Few top countries with installed capacity (MW) in the world, in Africa and that of East African nations

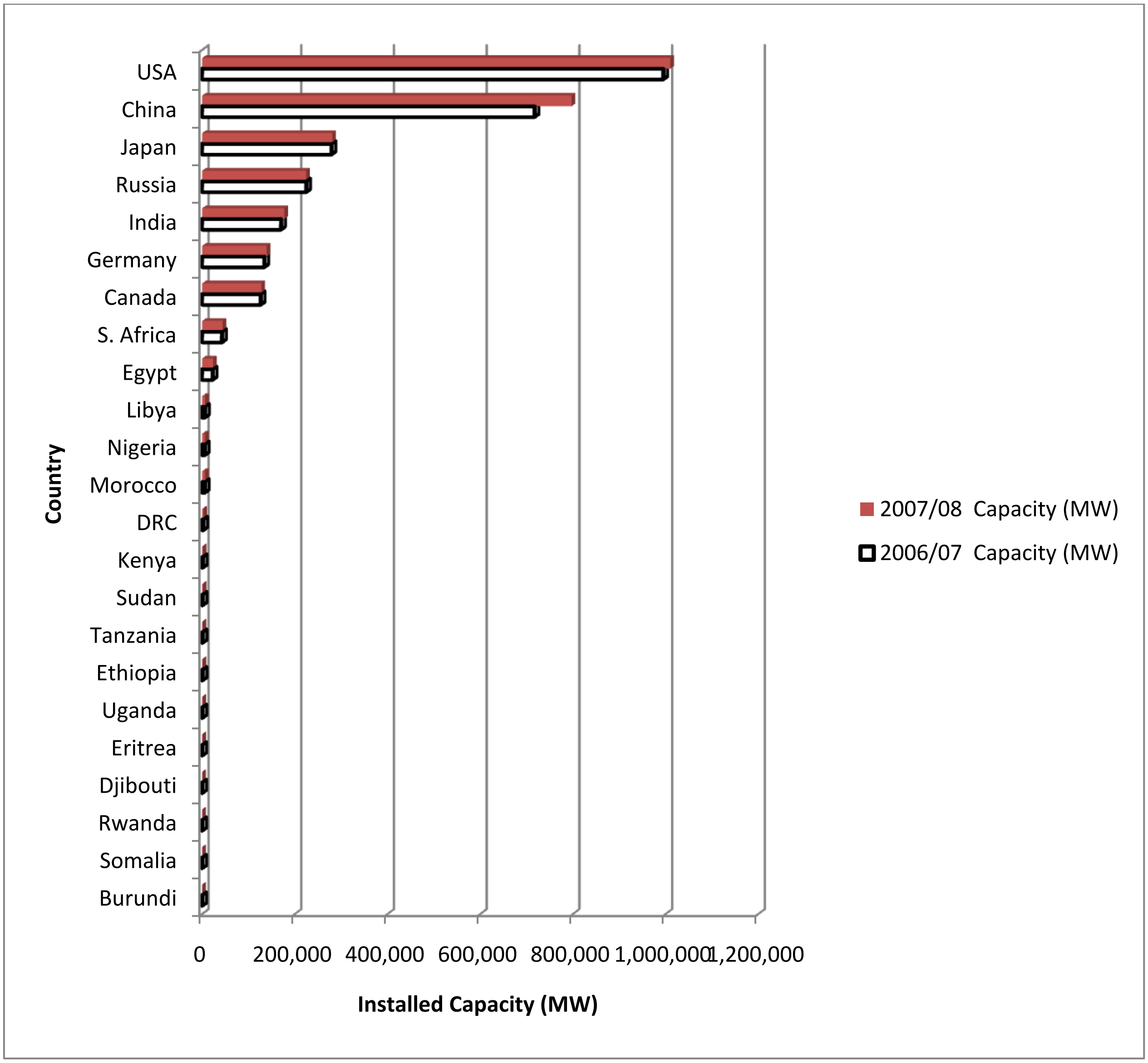
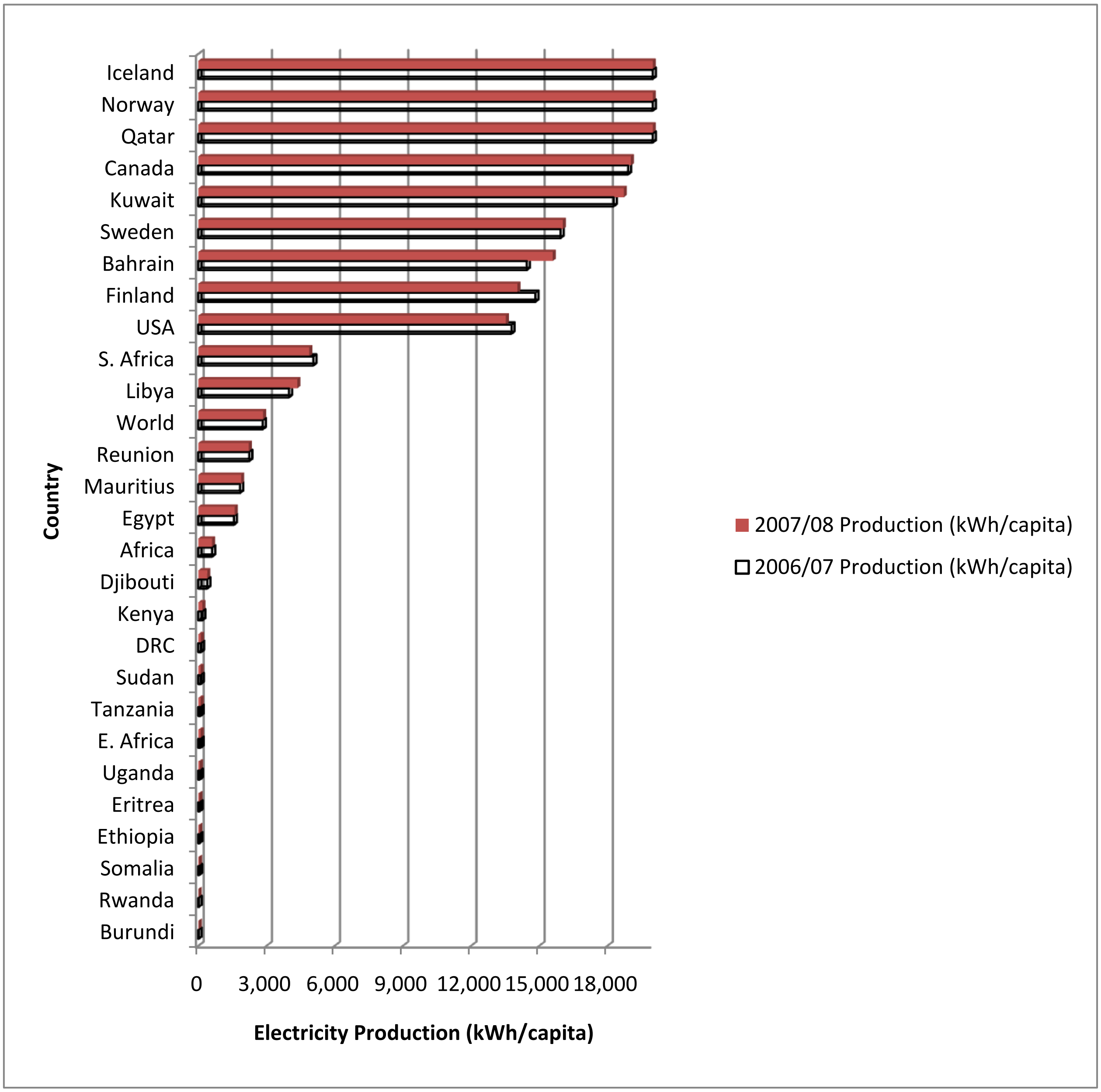


Chart 2: Few top countries with net production per capita (kWh/capita) in the world, in Africa and that of East African nations



Source: U.S. Energy Information Administration-Energy Review (2009)

In the above charts, it has been aimed to have general clue about electricity generation of some countries in the world compared with Ethiopia.

On the other hand, excerpt from EEPCo states that 500 kWh/year[2] is considered the average minimum level of consumption per- capita for reasonable quality of life.

Moreover, electricity supply has special characteristics which make the service unique as compared to other types of industry. The end product has to be delivered instantaneously and automatically upon the consumer's demand [9].

Therefore, to meet electricity requirements for customers, planning of the electric sector is of great importance since the decisions to be taken involving the commitment of large resources, with potentially serious economic risks for the electrical utility and the economy as a whole.

Power system planning is part of a more general problem, that of energy and economic development planning. Its objective is therefore to determine a minimum cost strategy for long-range expansion of the generation, transmission and distribution systems adequate to meet the electric energy requirements of a country over a given period within a set of technical, economic and regulations on energy policy constraints [9].

Power system planning has been mainly related to generation expansion planning. This is due mainly to the fact that investment in transmission lines is a relatively small fraction of the investment in the construction of power stations and that investment in the distribution of electric energy to customers [9]. Sourced from the EEPCo a 2006 master plan, it is verified that the capital cost for generation, transmission and distribution for 15 years of power system expansion planning in Ethiopia as of 1998 to 2012 is about 67%, 11% and 5% respectively. The rest 17% covers feasibility study and other miscellaneous costs.

The generation expansion planning problem is defined as the problem of determining WHAT, WHEN, and HOW MUCH new generation units should be installed over a long-range planning

[2] *EEPCo a 2006 master plan, August 2007*

horizon, to satisfy expected energy demand. This problem is a strategic planning problem for any country [3].

Generation expansion planning has historically addressed the problem of identifying ideal technology, expansion size, siting, and timing of construction of new plant capacity in an economic fashion and in a manner that ensures installed capacity adequately meets projected demand growth [16].

However, deregulation and current issues alter traditional generation expansion planning assumptions, models, and methods.

Now a day, the issue of global warming has great importance for the decision of power generation planning. To minimize the global warming, nations in the world have taken place summits, discussions and agreements. The Kyoto Protocol to the United Nations Framework Convention on Climate Change was the one and adopted in Kyoto, Japan, in December 1997 and entered into force on 16 February 2005. The Kyoto Protocol shares the ultimate objective of the convention to stabilize atmospheric concentrations of greenhouse gases at a level that will prevent dangerous interference with the climate system. The Kyoto Protocol allows countries to add to or subtract from their initial assigned amount, thus raising or lowering the level of their allowed emissions over the commitment period (up to 2012). These additions and subtractions are carried out in accordance with the so-called Kyoto mechanisms[3].

One of the mechanisms is Clean Development Mechanism (CDM). The CDM[3] is a project-based mechanism whose credits may be generated from emission reduction projects or from afforestation and reforestation projects in non assigned counties. On this precept, in Ethiopia, various projects are implemented. Humbo project is one example from which more than 5 million US dollar can be obtained[4]. For afforestation and reforestation projects, CDM mechanism is effective if the projects are implemented for the lands depleted before 1990.

[3] *Kyoto Protocol Reference Manual*

[4] *Opinion of expert in Ethiopian Environmental Protection Authority*

Other initiative has been proposed. It is Reducing Emissions from Deforestation and Forest Degradation (REDD).The main idea of such a REDD mechanism would be to provide incentives for developing countries to reduce deforestation and associated carbon emissions, which are greater than the entire global transport sector. Reductions in deforestation, degradation and the prevention of related carbon emissions is currently considered an effective mitigation option that could combat climate change and at the same time help to conserve biodiversity. Any such mechanism will require the systematic measuring and monitoring of national forests and their changes. Many developing countries have no or insufficient monitoring systems in place to observe their forest resources for participation in REDD[5]. Without REDD the 2^oC climate stabilization goal of the nations will not reach. Because deforestation accounts for about 18 percent of global GHG emissions—larger than the entire global transportation sector—reducing emissions from deforestation and forest degradation (REDD) has become a prominent potential mitigation strategy. The REDD concept is predicated on the assumption that forests will contribute to climate change mitigation only if their value increases to a level that makes protecting forests consistent with viable development strategies[6].

In early application of solutions, several methods have been proposed to solve the problem of generation expansion planning. The approaches have been focusing to minimize cost. This thesis is granted to profit maximization and cost minimization to be treated simultaneously for the optimization of power generation expansion planning with the incorporation of global issue.

1.2. Statements of the Problem

According to International Energy Agency (IEA) report (2009), fossil fuels remain the dominant sources of primary energy worldwide accounting for more than three-quarters of the overall increase in energy use between 2010 and 2030. This results high amounts of CO_2 emissions to the atmosphere and contributing adverse greenhouse effect. To reduce the non-renewable energy

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[5] *An assessment of national forest monitoring capabilities in tropical countries: Recommendations for capacity building Prepared by Martin Herold (m.h@uni-jena.de) GOFC-GOLD Land Cover Project Office Friedrich Schiller University, July 8, 2009*

6 Reducing Emissions from Deforestation and Forest Degradation ; an options assessment report- Prepared for the Government of Norway

-United Nations REDD program,2009

generation plants, the rapid change to renewable energy sources is being unlikely implemented due to their high investment cost(like for Ethiopia), availability, energy market, policy and regulatory frameworks established at national and international levels. Therefore, non-renewable energy resources plants will continue to provide a large proportion of world's commercial energy, and making the world to think about carbon dioxide capture and storage to control CO_2 emissions.

IEA (2010) reported that the broad scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2°C by 2020. For this, several governments have committed to provide funding support for demonstration and implementing projects to be responsible for reduction of CO_2 emissions. To reduce global emissions, the engagement of developing countries through capacity building and mapping of carbon storage potential, is vital.

Nevertheless, the energy sector in Ethiopia is composed of three main sub-sectors: biomass, petroleum and Electricity. Energy demand of the country is satisfied by wood fuel (77%), dung (7.7%), crop residue (8.7%), Bagasse (0.06%), charcoal (1.15%), electricity (1%), and liquid petroleum gas (LPG) (0.05%), and oil products (4.8%) [6]. The standing stock in forests and wooded areas in Ethiopia is estimated to be 1,200 million tons[7]. The annual yield from forest and wood land is estimated to be 30 to 40 million tons per year whereas actual consumption is 50 million tons per year[7]. The consequence of such wood fuel consumption is that the stock is declining by 1.25 % (taking the average annual yield of 35 million tonnes) yearly. This results in environmental degradation and global warming. Ethiopia is also losing benefits from carbon trading. The dung consumed for energy demand satisfaction is also significant amount. In Ethiopia, the estimates suggest that the reduction in agricultural productivity from lost nutrients associated with the use of animal dung for household fuel accounts for about a 7% reduction of agricultural GDP [4].

[7] *Ethio Resource Group (ERG) for Heinrich Boll Foundation (HBF) and Forum for Environment (FfE), Diversity and security for the Ethiopian Power System; A preliminary assessment of risks and opportunities for the power sector; August 2009.*

Another relevant issue is uncertainty in fuel price and its growth trend. Ethiopian fossil fuel usage covers about 5% of the total energy balance of the nation. As shown in figure 1, the trend of growth of the global price in USD per barrel of the crude oil between 1999 and 2010 is high and its fluctuation as well. This is significant to affect the country economic development.

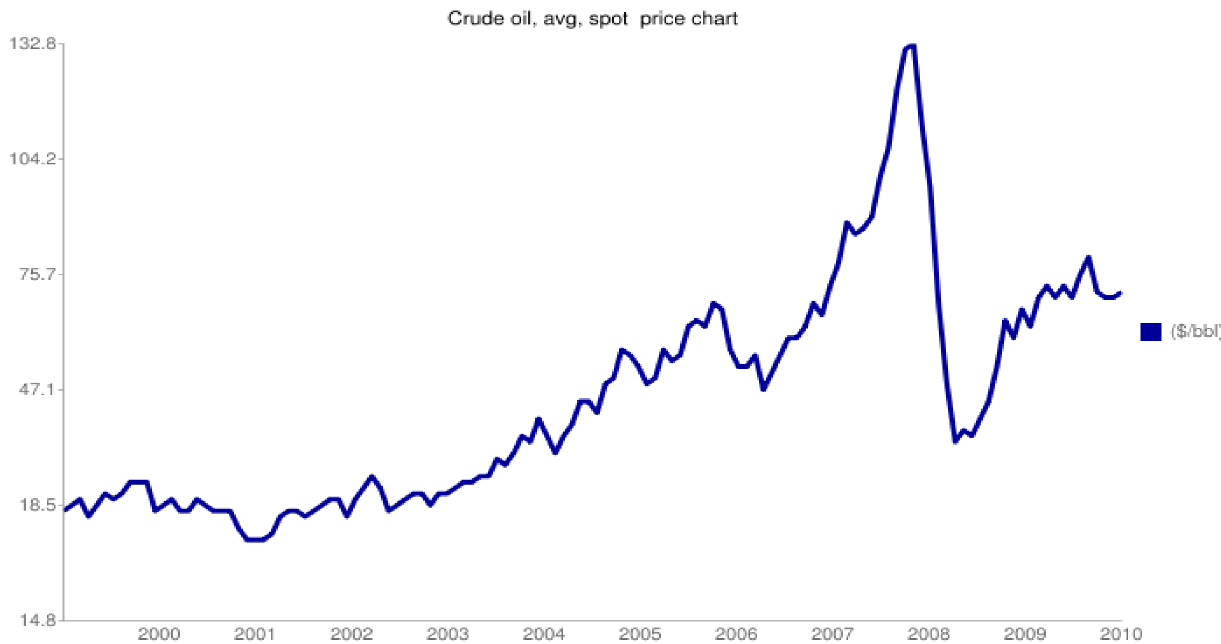

Figure 1: IEA report 2010

The researcher has looked through that, in Ethiopia, the energy demand is expected to be grown much more for the next five and above years due to population growth, social and economical developments and the governmental growth and transformation plans. Thus, following the previous trends of generation expansion planning will not satisfy the electricity demand.

To consider all the aspects mentioned above is the desire of any decision maker in generation expansion planning, and that is the motivation for the work presented in this thesis.

1.3. Objectives of the Study

The general objective of this study is to develop feasible model that solves the problems of generation expansion planning in Ethiopian electric power system for 10 years into the future. Specifically it is,

- ✓ To study the electric load forecast of the nation up to 10 years into the future for Ethiopian Electric Power System.
- ✓ To find out the relevant objectives which are to be optimized and constraints imposed in the Ethiopian power generation system and give explanation to them.
- ✓ To develop mathematical model and formulation for those revealed objectives and constraints in Ethiopian Electric Power generation system
- ✓ To identify solution technique to solve the developed model.
- ✓ To simulate the proposed model using MATLAB to justify the performance of the model

CHAPTER TWO

LITERATURE REVIEW

2.1. Electric Power System Expansion

Electricity is so basic to the world economy that certain electricity indices are used to express a country's economic standing (consumption or production of electricity per capita) and the standard of living enjoyed by a people (per capita electricity consumption in the domestic sector). Moreover, electricity supply has special characteristics which make the service unique as compared to other types of industry. The end product has to be delivered instantaneously and automatically upon the consumer's demand; except for pumped storage plants and electric batteries, technologies do not exist that can produce it economically at uniform rates, hold it in storage in large quantities, and deliver it under convenient schedules; insufficient capacity (shortage) or excessive capacity (idle capacity) have negative effects on the economy; the close inter-relation with economic and social factors imposes labour, environmental, financial and other constraints on the problem. Careful planning of the electric sector is therefore of great importance since the decisions to be taken involve the commitment of large resources, with potentially serious economic risks for the electrical utility and the economy as a whole [9].

Power system planning is part of a more general problem, that of energy and economic development planning. Its objective is therefore to determine a minimum cost strategy for long-range expansion of the generation, transmission and distribution systems adequate to supply the load forecast within a set of technical, economic and regulations on energy policy constraints [9, 14, 18].

Traditionally, power system planning has been mainly related to generation expansion planning. This is due mainly to the fact that investment in transmission lines is a relatively small fraction of the investment in the construction of power stations and that investment in the distribution of electric energy to customers too [14, 18].

Power system planning is part of a more general problem, that of energy and economic development planning. Its objective is therefore to determine a minimum cost strategy for long-range expansion of the generation, transmission and distribution systems adequate to supply the load forecast within a set of technical, economic and political constraints [14, 26].

2.2. Electric Demand Forecasting

An energy demand forecast is a measurement and estimate of historic, current and projected patterns of energy demand within a state. Accurate models for electric power load forecasting are essential to the operation and planning of a utility company [16, 17].

A forecast of the future eclectic demand and its geographic distribution is a prerequisite for generation planning [14]. There are different methods of forecasting load /energy demand which include trend analysis, end-use analysis and econometric analysis [16, 17].

Accurate models for electric power load forecasting are essential to the operation and planning of a utility company. Load forecasting helps an electric utility to make important decisions including decisions on purchasing and generating electric power, load switching, and infrastructure development. Load forecasts are extremely important for energy suppliers, ISOs, financial institutions, and other participants in electric energy generation, transmission, distribution, and markets [9].

2.3. Optimization

Optimization, or mathematical programming, refers to choosing the best element from some set of available alternatives. In the simplest case, this means solving problems in which one seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set. This formulation, using a scalar, real-valued objective function, is probably the simplest example; the generalization of optimization theory and techniques to other formulations comprises a large area of applied mathematics. More generally, it means finding "best available" values of some objective function given a defined domain, including a variety of different types of objective functions and different types of domains [27].

Normative economic decision analysis involves determining the action that best achieves a desired goal or objective. This means finding the action that optimizes (that is, maximizes or minimizes) the value of an objective function. In a production problem, the goal may be to find the combination of inputs (resources) that minimizes the cost of producing a desired level of output [22].

There are classical and numerical optimization techniques. The numerical optimization techniques include linear programming, non linear programming, dynamic programming, integer programming and stochastic programming [21].

Numerical optimization techniques of linear, dynamic, integer, non linear programmings have been used for electric power generation expansion planning models [5, 6, 8, 9, 14, 18].

2.4. Related Works

Until 1970's, the decision planners' task was to determine the best size, timing and type of generation plant to meet power demands. Today, the problem is more complex. There are several options consisting demand management, load growth uncertainty, fuel markets fluctuation and growth, cogeneration, government policy, small scale and renewable power resources, deregulated markets, and others [5].

Most generation expansion planning problems have been modeled as single objective programming problems which consider only the least cost [5]. Least cost strategy my reject certain objects entirely from the expansion plan due to higher capacity/ or energy cost and it favors the non-renewable energy resources.

Even though some works have been employed to incorporate multi objective models, carbon trading and benefit maximization approach were not considered [3, 4, 6].

CHAPTER THREE

MATERIALS AND METHODS

3.1. Materials

Materials have been used in this work are articles, theses and dissertations, reference and text books, recognized and regulated documents, media, softwares (MATLAB, Excel), internet, stationeries and personal computer.

3.2. Methods

Data collection, modeling, analyzing and simulation are the methods used. The following sections present each of these in detail.

3.2.1. Data Collection and Electric Demand Forecasting

Forecasting is one major work in generation expansion planning. This is done on the basis of economic and demographic status of the country. For the purpose of forecasting, the following data are collected from different sources.

Table 1: The annual energy sold by EEPCo for each tariff category

Tariff group	Annual energy consumed or sold (GWh)				
	2004/05	**2005/06**	**2006/07**	**2007/08**	**2008/09**
Domestic	730.6	795.7	1060.31	1029.32	1178.1
Commercial	527.6	583.9	703.44	732.05	737.48
Street Light	29.36	33.75	48.83	42.22	22.93
Large Industry LV	410.66	510.68	524.79	608.26	612.91
Large Industry HV	392.53	478.15	453.04	531.39	575.03
Own consumption	4.25	5.81	8.60	22.77	4.81
Total	2090.75	2402.18	2790.41	2943.24	3126.45

Source: EEPCo‘s a 2009 review

Note: The total electric energy consumed in 2003/04 was 1,847 GWh

Table 2: Number of customers of EEPCo connected to ICS and SCS

Number of customers of EEPCo					
Tariff group	**2004/05**	**2005/06**	**2006/07**	**2007/08**	**2008/09**
Domestic	820379	971411	1207894	1441304	1576964
Commercial	118494	138403	167654	207986	222698
Street Light	1739	2138	3056	3060	3260
Large Industry LV	10918	13216	15603	22908	24997
Large Industry HV	132	150	196	242	216
Own Consumption	1346	1466	1689	1834	1916
Total	953,008	1,126,784	1,396,092	1,677,334	1,830,051

Source: EEPCo‘s a 2009 review

Table 3: GDP growth rate of Ethiopia from 2002/03 to 2008/09 by sectors and overall

Sector	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
Agriculture	-10.5	16.9	13.5	10.9	9.4	7.5	6.4
Industry	6.5	0.7	9.4	10.2	10.2	10.4	9.9
Services	6	6.2	12.8	13.3	14.3	17	14
Total	**-2.1**	**11.7**	**12.6**	**11.5**	**11.5**	**11.6**	**10.1**

Source: National Bank of Ethiopia and Ethiopian Central Statistical Agency

Population Statistics

The most recent published national population and housing censuses for Ethiopia were held in May 1994 and May and November 2007. At those times, the total population counted was 53.4 million and 73.75 million respectively. An 86.3% of this population was classified as rural in 1994 and was so 83.9% in 2007. In contrast, at the 1984 census some 90% of the population was classified as rural (Ethiopian Central Statistical Authority (ECSA)). Based on this data, yearly urbanization growth rate between 1984 and 1994 was 0.41%, whereas, between 1994 and 2007, the growth rate was 0.20%. The estimated total population in 2020 would be about 105.28 million. The number of households in 2007 was about 16 million and the overall country household size was 4.7. The household size in 1994 census was 4.8. The household sizes of Addis Ababa and Dire Dawa were 4.1 and 4.4 respectively. The population growth rate from 1994 to 2007 was 2.7% and it is estimated the growth rate to be 2.6% (ECSA).

3.2.2. Electricity Demand Forecasting for Ethiopia in the Period of 2003/04-2019/20

An energy demand forecast is a measurement and estimate of historic, current and projected patterns of energy demand within a state. Accurate models for electric power load forecasting are essential to the operation and planning of a utility company [16, 17].

A forecast of the future eclectic demand and its geographic distribution is a prerequisite for generation planning [14]. There are different methods of forecasting load /energy demand which include trend analysis, end-use analysis and econometric analysis [16, 17].

3.2.2.1. Trend Analysis

Trend analysis extends past growth rates of electricity demand into the future. This method falls under the category of the non-causal models of demand forecasting that do not explain how the values of the variable being projected are determined. Here, we express the variable to be predicted purely as a function of time, rather than by relating it to other economic, demographic, policy and technological variables [16, 17].

3.2.2.2. End-Use Analysis

The end-use models for electricity demand focus on its various uses in the residential, commercial and industrial sectors. The end-use method is based on the premise that energy is required for the service that it delivers and not as a final good. The following relation defines the end use methodology for a sector:

$$E = S * N * P * H \tag{1}$$

where,

E = energy consumption of an appliance in kWh

S = penetration level in terms of number of such appliances per customer

N = number of customers

P = power required by the appliance in kW

H = hours of appliance use [16, 17].

3.2.2.3. Econometric analysis

This approach combines economic growth impact with statistical methods to produce a system of equations for forecasting energy demand. Taking time-series, causal relationships could be established between electricity demand and other economic and demographic variables. These variables could be population, GDP, number of customers, price [16, 17].

Note; Econometric models work best when forecasting at national, regional, or state levels. For smaller geographical areas, meeting the extensive data needs of the model can be a problem. This is because most utilities have oddly shaped service areas for which there is no published economic or demographic data.

3.2.2.4. Selection of Method for Forecasting

Trend analysis does not help to analyze why electricity demand behaves the way it does. It relies on past patterns of electricity demand to project future patterns of electricity demand. This simplified view of electrical energy could lead to inaccurate forecasts in times of change.

The shortcomings of end-use analysis are that most end-uses assume a constant relationship between electricity and end-use appliances. This might hold true over a few years, but over a 10- or 20-year period, energy savings technology or energy prices will undoubtedly change, and the relationships will not remain constant. It also requires extensive data, since all relationships between electric load and all the many end-users must be calculated as precisely as possible. If the data needed for end-use analysis is not current, it may not accurately reflect either present or future conditions, and this can affect the accuracy of the forecast. End-use analysis does not take price changes (elasticity of demand) in electricity or other competing fuels into consideration.

Therefore, mainly econometric and trend analyses are used. End-use analysis (where suitable) is also used in this thesis work.

3.2.2.5. Regression Analysis

The determinations of the relationship of dependent and other independent variables are found out. The database is developed from years 2003/04 to 2008/09 and then is used for the regression analysis. The database comprises:

- Yearly total energy consumption
- Yearly consumption by customer categories
- Yearly counted and estimated population and related data
- Yearly number of customers by customer categories

The independent variables, demographic, electrical and economic, include:

- Total GDP at constant prices
- GDP by major sector (agriculture, industry and services) at constant prices
- Number of customers by customer class
- Average electric consumption (kWh), by customer class
- Number of households (population)
- Time series

For the better accuracy of forecasting, starting with the year of 2003/04 is used. Because since then, the GDP turns into significantly sound and the electricity generation growth becomes raised up in Ethiopia

3.2.2.6. Regression Results

The regression relationships include:

- Sales versus an Income (GDP) variable;
- Sales versus the Price of Electricity;
- Sales versus Time (time trend);
- Sales versus combinations of the above variables;

- Energy demand versus time
- Energy demand versus number of customers and average consumption
- Energy demand versus number of households and average consumption
- Number of Customers versus time; and,
- Consumption per Customer versus Time.

The objective of the regression analysis was to determine an overall long term demand growth relationship for a variety of consumption categories.

The long term energy forecast requires growth rates for total demand by principal sales category. These growth rates are determined from the elasticities obtained in the regression analysis and the growth in the relevant independent variable. The regression analyses were carried out on the different sales categories, explanatory variables and time periods.

3.2.2.7. Population and Energy Demand

Undoubtedly, population growth has strong ties with energy demand. As population increase, total energy consumption will increase. However, electricity consumption was centered in urban areas in Ethiopia context. But, currently, electricity consumption is being distributed in rural areas too. In 1994 and in 2007 of the national population and housing census, the ECSA reported that 1 % and 2.5% respectively of the total rural population were using electricity for lighting in rural areas. On the view of this figure, the rural households who use electricity can be obtained.

The regression analysis in this thesis work considered the number of households and household growth, because electricity demand is satisfied and supplied for households not for individual population. So, it is found out first knowing the projection population status by using estimated population growth rate (2.6%) and then taking the average value of Addis Ababa and Dire Dawa household sizes for determining number of urban households in each year within proposed period.

3.2.2.8. Economic Growth and Energy Demand

Currently the government has undertaken various measures to improve the productivity of the agricultural, industry and service sectors. The average annual GDP growth rate from 2002/03 to 2008/09 was 9.6%. In each economic sector and overall growth rate is shown in Table 3; and in the next 5 years, Ethiopian government planned that the GDP growth rate would be 11% in basic growth plan and 14.9% in higher target growth plan[8].

Economic growth rate has an impact on electricity consumption. As income rises, consumers tend to purchase more electricity consuming goods. As a result, electricity consumption tends to increase. The income elasticity in the regression equation is, therefore, considered and it describes the increasing or decreasing tendency of electricity consumption effect due to income growth accordingly. If the elasticity is, for example, 0.9, this means that an 11% rise in GDP results in a 9.9% rise in electricity consumption of the customers.

3.2.2.9. Prices Change and Energy Demand

From the 1952 tariff amendment until 1994 there had been only four revisions but percentage increases had been as high as 54%. The 1994 change was the first of a 5 year package of tariff adjustments intended to increase the average tariff to US 0.06 $/kWh. The increase was to occur in three steps of 20%, 35% and 45%. The revision was also to remove the existing cross-subsidy to domestic customers. The first change, in October 1994 raised rates by an average of 12.7%. The second revision raised rates a further 39% in April 1997. The final increment, implemented in April 1998 raised rates to 32.5% to achieve the US 0.06 $/kWh plateau[9]. For the past 15 years there has been no tariff amendment.

Price change can result in to a decrease in the sales of electricity (decrease of consumption).

Countering of income elasticity effect is price elasticity, the tendency for customers to limit their consumption if real prices increase. For a price elasticity of -0.50, for instance, a 10% increase in

[8] Ministry of Finance and Economics Development, GTP(2010/11-2014/15), Volume I, main text, November 2010, Addis Ababa

[9] *Unpublished paper from EEPCo planning office*

price results in a 5.0% decline in consumption Thus under normal circumstances the price elasticity is negative.

EEPCo has been attempting to adjust the tariff rates in order to meet its current and future financial requirements. Assuming no tariff change, price elasticity and its effect on electricity consumption can be ignored in this thesis work.

3.2.2.10. Average Consumption per Customers

Implicitly in the historical data and therefore in the forecast, new customers in any given year are assigned a consumption rate equal to the average consumption rate calculated for all existing connections in that year. Of course, this assumption offsets effects of adding a mix of low income consumers, middle income and higher income consumers from general population growth. It is used where information and data are not available.

Thus, average consumption per customer in the years of 2004/05 and 2008/09 is obtained using the data in Table 1 and Table 2 and shown in Table 4.

Table 4: Average consumption per customer in EEPCo power supply system within the period 2004/05 and 2008/09

Year	**Tariff Group**					
	Domestic (KWh)	**Commercial (MWh)**	**Street Light (MWh)**	**Large Industry LV (MWh)**	**Large Industry HV (GWh)**	**Own Consumption (MWh)**
2004/05	890.56	4.45	16.88	37.61	2.97	3.16
2005/06	819.12	4.22	15.79	38.64	3.19	5.09
2006/07	877.82	4.20	15.98	33.63	2.31	3.08
2007/08	714.16	3.52	13.80	26.55	2.20	3.10
2008/09	747.07	3.31	7.03	24.52	2.66	2.51

However, the last trend (from 2004/05 to 2008/09) of EEPCo's power supply shows declining of electricity consumption per customer in each tariff group of EEPCo.

From Table 4, we can see that the electricity consumption per customer in each tariff group is declined from the year 2004/05 to 2008/09. From the experience of our observation also, there has been faced power disruption for the last few years. Therefore, it is acceptable to take the average consumption per customer at the years of 2004/05 or 2005/06. At those years, the customers were supplied as much as they demanded.

Therefore, for domestic, commercial, LV industry, HV industry, street light and own consumption, it has been taken as 891 kWh, 4.45 MWh, 38.64 MWh, 3 GWh, 17 MWh and 5.09 MWh respectively (unless other way is obtained).

3.2.2.11. Domestic Demand Forecasting

As depicted in Table 3, the number of customers of electricity consumption has been increasing in Ethiopia. From 2004/5 to 2008/09, the number of customers of EEPCo in domestic sector increases on the average by 18% per year.

In this thesis, there are two scenarios developed in domestic electricity demand forecasting.

3.2.2.11.1. Stretched Forecasting (Scenario-1 for Carbon-Trade Consideration)

The growth of electric consumption will increase much more than the last trends, because of three reasons.

Firstly, according to the government future plan and the last trends of growth of GDP, there will be expected a sustained economic development. As described before, as income of the people is high, customers tend to purchase more electricity consuming goods. This results in increasing of electric energy demand by the people.

Secondly, there are numbers of domestic apartments being built. These apartments need more electricity consumption than the earlier traditional energy consumption (wood and charcoal consumption for cooking).

Finally, the researcher's aspiration is that every household in urban areas will be satisfied the energy demand from electricity.

Therefore, the total households in urban areas are considered in that they demand the electricity for energy requirement. The households are determined from the estimated population growth (2.6%) and urban household size (assumed the average value of sizes of Addis Ababa and Dire Dawa of 2007 census constant. Because, the annual variation is insignificant. For example, the household size of the country in 1994 was 4.8 and 4.7 in 2007). Therefore, the average household size of both cities is 4.25 and it is assumed for all urban areas of the country. Number of urban households since 2006/07 up to 2019/20 is shown in Table 5.

Table 5: The estimate of total population, share of urban population compared with the total population, urban population and number of urban households in Ethiopia since 2006/07 to 2019/20

Year	**2006/07**	**2007/08**	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**
Total population (Millions)	73.5	75.41	77.37	79.38	81.45	83.56	85.74
Share of urban population (%)	16.10%	16.20%	16.30%	16.40%	16.50%	16.60%	16.70%
Urban population (Millions)	11.83	12.22	12.61	13.02	13.44	13.87	14.32
Number of urban households('000)	2,784	2,874	2,967	3,063	3,162	3,264	3,369
Year	**2013/14**	**2014/15**	**2015/16**	**2016/17**	**2017/18**	**2018/19**	**2019/20**
Total population (Millions)	87.97	90.25	92.60	95.01	97.48	100.01	102.61
Share of urban population (%)	16.80%	16.90%	17.00%	17.10%	17.20%	17.30%	17.40%
Urban population (Millions)	14.78	15.25	15.74	16.25	16.77	17.30	17.85
Number of urban households('000)	3,477	3,589	3,704	3,823	3,945	4,071	4,201

Thus, from the table, the number of urban households in 2009/10 was 3.063 million and will be 4.201 million in 2019/20. It will increase averagely by 4.15% per year.

Once the number of households determined, it is to find electricity consumption per urban household, and it is carried out as follows.

Energy consumed by domestic appliances takes a significant part of the total energy demand for private households. The estimation is limited to costumed household appliances, namely lighting, ovens for Injera baking and cooking, refrigerators, television, radio and water heaters. Other appliances including freezers, washing machines, dishwashers, tumble dryers, computer, etc are used for household function as income of the customers is increased. Therefore, average yearly electrical energy per household is obtained and this is presented as under.

Lighting: Lighting will continue to be important in the future due to the present low level of electrification and the fact that lighting will be the main end use in new residential connections (low income and rural customers). The monthly consumption of an incandescent and a fluorescent lighting in household are 7 kWh and 15 kWh[10] respectively. Taking the mean of 11 kWh and assuming average of five bulbs used in each urban household, annual demand per household is an average of 660 kWh.

Injera baking: With growing urban population and increasing incomes the number of households with electric *mitad* is growing rapidly.

A household survey in Addis Ababa estimated 87% market penetration for the electric *mitad* in 2009. It was 13% coverage in 1984. According to earlier surveys electric *mitad*s are rated 2 to 4 kW with mean of 2.5 kW[10] and owners use the *mitad* twice a week for 2-hour baking sessions. Therefore, in one household, 1,040 kWh electricity energy is consumed in a year.

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[10] *Ethio Resource Group (ERG) for Heinrich Boll Foundation (HBF) and Forum for Environment (FfE), A preliminary assessment of risks and opportunities for the power sector,2009*

- Melessaw Shanko1 and Jonathan Rouse, The human and livelihoods cost of fuel-switching in Addis Ababa, , Megan Power, P.O. Box 180884, Addis Ababa, Ethiopia. Email: j.r.rouse@gmail.com,

Cooking: Cooking ovens are rated to 0.5 kW -1.5 kW. Its operation is three times a day for an average of 1 hour. Taking the mean rate of 1 kW, the consumption of cooking oven is about 1,095 kWh in a year.

Water heating: Mid and high income households in cities use electric boilers for water heating. Boilers are rated between 0.5 kW to 1.5 kW and are operated once a week (mid income) or daily (high income) for an average of 2 hours per session[11]. Contribution to total residential customer sales is small. However, penetration levels are expected to increase rapidly as incomes grow thus increasing demand from this end use.

Thus, taking the mean rate of boilers as 1 kW, 1 kW* 2hrs/day*365 days=730 kWh[12] for high income and 104 kWh for mid income levels per household is consumed in a year, and no consumption for low income ones. Assuming equal households in each income level, and taking average, the average annual consumption per household is 278 kWh in a year.

Radio and television: According to 2007 census, the coverage of radio and television in urban areas was 68.5 % and 27.5 % respectively of the housing units. The figures were 47 % and 6.6 % respectively in 1994 national census. The annual growth rate is 4% for radio and 26% for television. Based on this status of dissemination, in two, three years, every family in urban areas has television. The radio coverage will also be big figure within two years.

Average wattage of television used in Ethiopia is 200 W[11] and is 20 W that of radio. If the two devices operate for 4hours per day, annual consumption will be 292 kWh and 30 kWh respectively.

Refrigerator: It is not known how many housing units do have refrigerator. Annual consumption of refrigerator is 763 kWh[12]. Assuming average of one tenth of housing units in urban using refrigerator, annual electricity consumption in each household is 76 kWh.

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[11] *Ethio Resource Group (ERG) for Heinrich Boll Foundation (HBF) and Forum for Environment (FfE), A preliminary assessment of risks and opportunities for the power sector,2009*

[12] *United Nations Environment Programme collaborating center on energy and environment Riso National Environment Laboratory, Nov. 1997 referred Jannuzzi et.al. (1995)*

The total consumption of above appliances per urban household in a year, therefore, is about 3,458 kWh.

As discussed in section 3.2.2.6, the growth rate of housing units in rural areas use electricity is averagely by 0.14% yearly. The average annual electricity consumption of each household is about 200 kWh [1]. Based on this, the following electric energy demand is obtained.

Table 6: The estimate of total population, share of rural population compared with the total population, rural population, rural households use electricity and the electricity demand in GWh of rural areas in Ethiopia since 2006/07 to 2019/20

Year	**2006/07**	**2007/08**	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**
Total population (Millions)	73.5	75.41	77.37	79.38	81.45	83.56	85.74
Share of rural population (%)	83.90%	83.80%	83.70%	83.60%	83.50%	83.40%	83.30%
Rural population (Millions)	61.67	63.19	64.76	66.36	68.01	69.69	71.42
Number of rural households(‘000)	12,333.3	12,638.7	12,951.7	13,272.3	13,602.2	13,937.8	14,284.3
Percentage of rural households use electricity	2.63%	2.77%	2.90%	3.04%	3.18%	3.31%	3.45%
Rural households(‘000) use electricity	324	350	376	403	433	461	493
Electricity demand GWh	64.8	70	75.2	80.6	86.6	92.2	98.6
Year	**2013/14**	**2014/15**	**2015/16**	**2016/17**	**2017/18**	**2018/19**	**2019/20**
Total population (Millions)	87.97	90.25	92.6	95.01	97.48	100.01	102.61
Share of rural population (%)	83.20%	83.10%	83.00%	82.90%	82.80%	82.70%	82.60%
Rural population (Millions)	73.19	75	76.86	78.76	80.71	82.71	84.76
Number of rural households(‘000)	14,638.2	14,999.55	15,371.60	15,752.66	16,142.69	16,541.65	16,951.17
Percentage of rural households use electricity	3.58%	3.72%	3.86%	3.99%	4.13%	4.26%	4.40%
Rural households(‘000) use electricity	524	558	593	629	667	705	746
Electricity demand GWh	104.8	111.6	118.6	125.8	133.4	141	149.2

The estimated result of urban households (Table 5) and average consumption per urban household (3458 kWh) combined with electricity demand by rural areas (Table 6) gives the forecasted electric energy in domestic sector of EEPCo tariff category and is depicted in Table 7. The staring year for this scenario is taken as 2011/12. Before 2011/12, the demand is determined on the basis of previous trends.

Table 7: The forecasted result of electric demand by domestic sector in Ethiopia since 2011/12 to 2019/20

Year	**2011/12**	**2012/13**	**2013/14**	**2014/15**	**2015/16**
Number of urban households(‘000)	3,264	3,369	3,477	3,589	3,704
Electric energy demand by urban domestic sector (GWh)	11,287	11,650	12,023	12,411	12,808
Electric energy demand by rural domestic sector(GWh)	92.2	98.6	104.8	111.6	118.6
Total electric energy demand by domestic sector (GWh)	11,379	11,749	12,128	12,523	12,927
Year	**2016/17**	**2017/18**	**2018/19**	**2019/20**	
Number of urban households(‘000)	3,823	3,945	4,071	4,201	
Electric energy demand by urban domestic sector (GWh)	13,220	13,642	14,078	14,527	
Electric energy demand by rural domestic sector(GWh)	125.8	133.4	141	149.2	
Total electric energy demand by domestic sector (GWh)	13,346	13,775	14,219	14,676	

On this result, the electric demand in domestic sector will grow up averagely by 25.71% in the years of 2010/11 to 2019/20.

3.2.2.11.2. Target Forecasting (Scenario-2)

In this scenario, the forecasting is determined on the basis of the growth trend of number of customers and economic analysis. As explained before, the number of customers in domestic tariff category becomes increased and it accounts for 18% growth rate. The following equations are used for knowing the growth of number of customers in domestic subsector.

$$cus_t = b_0 + b_1 * t \tag{2}$$

where,

$cus_t = number\ of\ customers\ at\ year\ t$

$$b_1 = \frac{n * \sum(t_i * cus_i) - (\sum t_i) * (\sum cus_i)}{n * \sum t_i^2 - (\sum t_i)^2}$$

$$b_0 = \frac{\sum cus_i}{n} - \frac{b_1 * \sum t_i}{n}$$

$cus_i = number\ of\ customers\ at\ i^{th}\ year$

$t_i = i^{th}\ year$

$n = number\ of\ samples$

The electric demand of the sector is obtained by equation (3).

$$dem_{tc} = avecon_c * cus_t \tag{3}$$

where,

$dem_{tc} = total\ demand\ by\ customer\ category\ at\ \ year\ t$

$avecon_c = average\ consumption\ in\ customer\ category$

Using the data of number of customers in Table 2 of domestic sector in equation 2, the following equation is obtained.

$$cus_t = -3.97 * 10^8 + 198306.3 * t \tag{4}$$

Substituting equation (4) and average consumption of domestic sector determined previously (Table 6) in equation (3), we will get equation (5).

$$dem_{tc} = -3{,}537 * 10^5 + 177 * t\ (GWh) \tag{5}$$

In this scenario, the electric demand by domestic sector is increased averagely by 11.33% yearly.

3.2.2.12. Income Elasticity

As explained in previous section, as GDP increases, demand of electricity will increase. Thus, income elasticity is determined to forecast the demand in domestic electricity consumption. Cobb Douglas production function is employed here.

$$E = aY^{\alpha}P^{-\beta} \quad (6)$$[a]

where,

E=energy demand

Y=income (GDP)

P=price of energy

a=coefficient (total factor productivity level)

α=income elasticity=ΔE/E/(ΔY/Y)=%change in E/%change in Y

β=price elasticity= ΔE/E/(ΔP/P)= %change in E/%change in P

Since there is no price change consideration, equation (6) is reduced to

$$E = aY^{\alpha} \quad (7)$$

Equation (7) can be written in the linear regression form as

$$\log E = \log a + \alpha * \log Y \quad (8)$$

$$y = b_o + b_1 x \quad (9)$$

where,

$$y = \log E$$
$$b_o = \log a$$
$$b_1 = \alpha$$
$$x = \log Y$$

Using equation (9) and taking the GDP growth rate of Ethiopian economy for the last years of 2004/05 to 2008/09, the regression result gives the income elasticity in domestic sales as 1.16.

So, equation (5) is reformulated as

$$dem_{tc} = -7{,}640 * 10^5 + 382 * t\ (GWh) \quad (10)$$

[a] *Cobb Douglas Production Function*

For GDP growth of 14.9% (the higher target GDP plan), the result of electricity demand is increased by 38.25% each year as of 2009/10 to 2019/20.

3.2.2.13. Commercial Sector Demand Forecasting

As with the domestic sales, commercial sales has a strong correlation with GDP, price change and the number of customers. Once again assuming no tariff change, the regression analysis is limited to GDP and number of customers.

The number of customers is correlated with time. To know more accurate the commercial customers demand, it needs extensive surveys. Thus, the projection of number of customers is limited to the past trends in EEPCo expansion and selling history for commercial customers. The equations of (2), (3) and (9) are used to determine demand growth. The income elasticity is found as 0.82.

Thus, the following equation (11) is obtained.

$$dem_{tc} = -247{,}517 + 124 * t \ (GWh) \tag{11}$$

From the above results, the electricity demand in commercial category is increased averagely by 32.6% per year from 2009/10 to 2019/20.

3.2.2.14. Industrial Sector Demand Forecasting

Ethiopia has planned transformation and growth for the next five years. According to the GTP, it has been planned several factories will be established and much products are expected from those industries. It is known that intensive energy is consumed in factories. But, the intensity of energy consumption varies with type of factory. Table 8 shows the average specific electricity consumption taken from some factories. The values are chosen for using the demand estimation of the factories found in Ethiopia. So it is to know specific electricity consumption for demand forecasting of industry sector. Therefore, the demand is resolved by taking into account the specific electricity consumption, the number of factories to be established and/ or the products to be found from the factories in each year.

Table 8: Some factories with their electricity consumption (kWh/ ton of product)

S.No	Type of factory	Specific electricity consumption (kWh/ton of product)	Remark
1	Agro processing	0.1524 GWh/yr/factory[13]	
2	Cement	110[14]	
3	Iron and steel	550[15]	
4	Textile	221.1/1000 spindles[16]	
5	Leather	13 kWh/pc[12]	
6	Sugar	80[17]	
7	Pharmaceutical	1.565 GWh/yr/factory[18]	

EEPCo has two tariff categories in industry sector consisting LV-industry and HV-industry. In Table 9, the listed out factories are grouped under HV-industry category. Therefore, the demand is estimated by applying the methods of partial-end-use and econometric analyses. Whereas those of manufacturers grouped under LV- industry, because of data limitation, the estimation is treated by applying trend and econometric analyses methods.

The following table shows the summarized Growth and Transformation Plan (GTP) for industry for the next five years sourced from GTP of Ministry of Finance and Economy Development and corresponding estimated electricity consumption done by the researcher.

The demand is estimated by taking specific electricity consumption from local factories or other countries and the planned products (shown in Table 9). If the data are not available through either

[13] www.wikipidea

[14] *Muger Cement Factory*

[15] *India's Iron and Steel Industry: Productivity, Energy Efficiency and Carbon Emissions -Katja Schumacher and Jayant Sathaye Environmental Energy Technologies Division, October 1998*

[16] (Mikio Uno: Textile Engineering Vol.28 No.5 (1975))

[17] *Metehara sugar factory, yearly bill supplied from the national grid*

[18] *Pharmaceutical company, France, www.osram.com/energyaudit , retrieved on 18/03/2011*

of the two alternatives, the forecasting is carried out by considering the number of factories and the average demand (3 GWh/yr/customer) previously determined.

Table 9: The Ethiopian government five-year plan in industry sector and the corresponding electricity consumption

	Type of Factory	2002 (ECSA)*	2003	2004	2005	2006	2007
1	Textile (No of factories)	64	76	88	100	112	112
Electricity consumption (3 GWh/factory)		*192*	*228*	*264*	*300*	*336*	*336*
2	Leathers-Shoes product(million pairs)	9.22	9.22	13.18	15.39	17.98	21.04
	Clothes (numbers- '000)	8.56	8.56	51.12	146.4	260.8	455.0
Electricity consumption (13 kWh/pc)		*120*	*120*	*172*	*202*	*237*	*280*
3	Sugar (million ton)	0.3375	0.3801	0.7375	0.9785	1.3352	2.2520
Electricity consumption (80 kWh/ton of sugar)		*27*	*30*	*59*	*78*	*107*	*180*
4	Iron and steel(kg per capita)	10.68	14.23	17.78	22.23	27.75	34.72
Electricity consumption (550 kWh/ton)		*457*	*634*	*812*	*1039*	*1328*	*1700*
5	Cement (million ton)	2.7	9.34	13.6	13.6	17	27
electricity consumption(110 kWh/ton)		*297*	*1027.4*	*1496*	*1496*	*1870*	*2970*
6	Chemicals (No of factories)	73	73	75	75	78	81
electricity consumption(1.565 GWh/factory)		*114*	*114*	*118*	*118*	*122*	*127*
7	pharmaceutical (No of factories)	7	7	9	11	14	17
electricity consumption(1.565 GWh/factory)		*11*	*11*	*14*	*17*	*22*	*27*
8	Agro processing (No of factories)	50	54	61	68	77	80
Electricity consumption(0.1524 GWh/factory)		*7.62*	*8.23*	*9.3*	*10.36*	*11.3*	*12.2*
Total		**1,226**	**2,173**	**2,944**	**3,260**	**4,033**	**5,632**

* *ECSA-Central Statistics Agency*

Taking the total electric demand by HV industry class from Table 9 and using regression equations (2), (3) and (9), we will have the following equation (12).

$$dem_{tc} = -1{,}596{,}150.58 + 798 * t \ (GWh) \quad (12)$$

Due GDP growth impact on demand (income elasticity is obtained as 0.9); equation (12) is reformulated as equation (13).

$$dem_{tc} = -3{,}032{,}686 + 1{,}516 * t \ (GWh) \quad (13)$$

On the aspect of growth of customers in industry sector, from the 2003/04 to 2009/10, the customer grew up by 37.9 %. This is done by using linear regression equations of (2), (3) and (9). In this period the demand is determined by taking the average consumption per customer obtained before (Table 5) as 3 GWh.

On this base, the demand is increased by 13.5 % from 2003/04 to 2009/10 and by 43.64 % from 2010/11 to 2014/15. The result of the period in 2009/10-2014/15 is done on the linear regression method to project further up to 2019/20. Thus, from the result, the annual demand growth in HV industry sector in the years 2009/10 to 2019/20 is 41.7 %.

For LV industry sector, equations (2), (3) and (9) and average consumption of LV industry determined before (Table 5) are used. Therefore, the following equation (14) is obtained.

$$dem_{tc} = -309{,}120 + 146 * t \ (GWh) \quad (14)$$

3.2.2.15. Public Lighting and Own Consumption Forecasting

Public lighting and Own consumption are insignificant to elasticity to income and price, because demand is necessity. So, number of customers is correlated with time.

Therefore, using equations (2) and (3) and average consumption per customer for these sectors (Table 5), demand equations for public lighting and own consumption are

$$dem_{tc} = -13{,}480 + 6.74 * t \quad (15)$$

and

$$dem_{tc} = -1{,}532 + 0.77 * t \quad (16)$$

respectively.

3.2.2.16. Generation and Lose Rate

The power loss in Ethiopia was about 20% in 2003/04, which is much higher than the international average, 12-13 %. Most of the loses happen during distribution from the national grid to end users[19].

The sales forecasts determined are converted to a net energy generation requirement on the basis of the average system loss rate. At present EEPCo is undertaking urban distribution rehabilitation works at various major cities and towns so as to reduce the existing high loss rate to a reasonable value. The recent year's average ICS loss rate is around 16%, (Table 10).

Table 10: Electricity production, consumption and its lost in EEPCo power system in the years of 2004/05 to 2008/09

Year	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
Electric Production in GWh	2,316	2,589	2,897	3,321	3,547	3,728
Electric Consumption in GWh	1,847	2,095	2,408	2,799	2,966	3,131
Lost in percentage	20%	19%	17%	16%	16%	16%

Source: EEPCo's a 2009 report

3.2.2.17. Reserve Capacity

All utilities must plan to have a certain amount of reserve generation capacity to supply the needs of their power customers in the event that a portion of the installed generating capacity is unavailable. The power system is disrupted due to outages, planned outages in case of scheduled maintenance and unplanned outages in case of forced conditions in some units.

[19] *Study on the Energy Sector in Ethiopia translated by the Embassy of Japan in Ethiopia based on an original report written in Japanese, September, 2008*

Reserve generating capability is also needed to supply any expected growth in the peak needs of electric utility customers. Therefore, it is recommended that the utilities would satisfy a 15% reserve requirement in hybrid system and 15-25% reserve in thermal dominant system [19].

Thus, in this paper, due to not thermal dominant system in Ethiopian electric power system, 15% of the installed capacity reserve is used.

3.2.2.18. Forecasted Result

Above all, the demand of electricity consumption in Ethiopia as of the base year 2003/04 to 2019/20 by each customer category and their total are determined using the above results and the following equations (17), (18) and (19).

$$dem_t = \sum_{c=1}^{C_T} dem_{tc} \tag{17}$$

where,

$dem_{tc} = total\ demand\ by\ customer\ category\ at\ \ year\ t$

$dem_t = total\ demand\ of\ total\ customer\ categories\ at\ \ year\ t$

The generation should be determined by regarding system loss rate and reserve capacity explained and determined in previous sections. The following general equations resolve the total demanded generation.

$$gen_t = dem_t + loss * dem_t \tag{18}$$

$$gen_{Tt} = gen_t + rem^* gen_t \tag{19}$$

where,

$gen_t = total\ demanded\ generation\ considering\ loss\ rate$

$gen_{Tt} = total\ demanded\ generation\ with\ reserve\ capacity\ at\ \ year\ t$

$$dem_t = total\ customers'demand\ at\ \ year\ t\ (without\ loss\ and\ reserve)$$

$$rem\ = reserve\ capacity\ multiplier\ (0.15)$$

On this base, the total electric demand forecasted result is shown in figure 2. This figure shows the forecasted demand by scenario-1, scenario-2 and that of EEPCo plan. The detail result is shown in Table A5 of Appendix A.

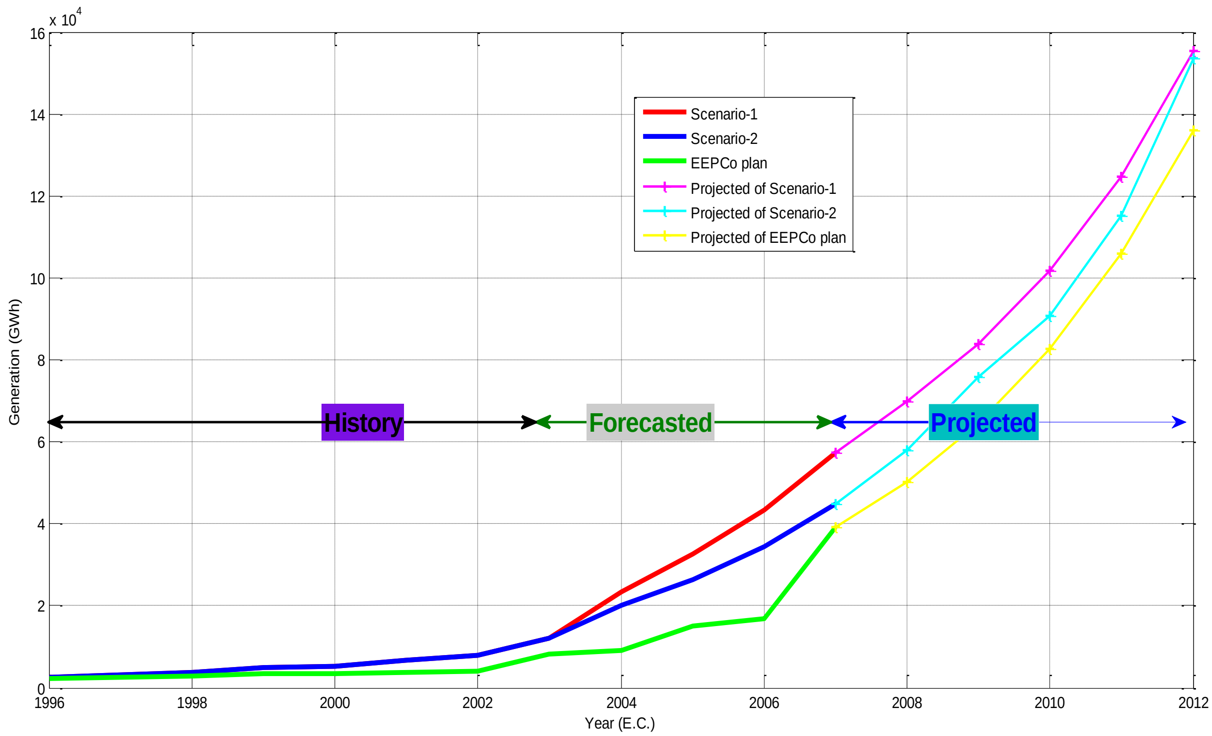


Figure 2: The result of Electricity Demand Forecasted (in GWh) and that of EEPCo plan in the periods of 2003/04 to 2019/20

3.2.3. Evaluation of the Energy Resources in Ethiopia for Electricity Generation

The abundance of the resource and its relatively low cost of energy production make hydropower the first choice for system expansion[20]. However, Ethiopia also has other renewable and non-renewable energy resources that are may be utilized for power generation. The renewable resources include geothermal, wind, solar, and biomass (including biofuels and biogas). Proven reserves of coal and natural gas are also available in economic quantities.

Evaluation of energy resources both in existing and candidate power plants needs extensive works and time. Therefore, already studied and estimated potential for power generation in the country has been used for this thesis work.

Table 11 indicates the estimates of the gross and economic potential for power generation in Ethiopia. At the forth column, it is estimated the energy to be produced by considering the plant factor at 53% (the average plant factor of existing, committed and candidate power plants).

Table-11: Estimated gross and economic potential for power generation and energy production from different energy resources in Ethiopia

Energy resources	Gross potential (MW)	Economic potential (MW)	Average plant factor	Energy estimation (GWh/year
Hydro	184,000[20]	45,000[20]	53%	208,926
Geothermal	5,000[21]	1,000[22]	79%	6,920
Wind	169,000[20]	10,000[19]	26%	22,776
Solar	100MWe/km^2	100[20]	20%	175
Bioenergy	530[20]	530[20]	68%	3,157
Coal	NA[23]	100[20]	68%	596
Oil	430,000 bbl[20]	NA	82%	Not estimated
Natural gas	NA[20]	600[20]	85%	4,468
Total		**57,330**		**247,018**

[20] *Ministry of Water and Energy-2010.*
[21] *ETV-29/03/2011*
[22] *Tract prepared by EEPCo on the day of Tana Beles Hydro Power Plant inauguration*
[23] *NA=information is not available*

Currently, the national energy balance indicates that biomass fuels (wood, charcoal, agricultural residue and animal waste) meet 94% of total energy consumed. The contribution of petroleum fuels and electricity to the national energy balance shares 5% and 1.0% respectively [4, 7].

At the year 2009/10, the national energy consumption from electricity (1% of the total national energy balance) is about 4,101 GWh per year. The total energy consumed by the nation is about $\frac{4101}{0.01} \approx 410{,}100$ GWh per year.

Thus, if the economical potential resource for electricity estimated energy were exploited, 60% (very large amount!!!) of the national energy balance could be covered by electricity.

3.2.4. Modeling

Power generation expansion planning inherently involves multiple, conflicting and disproportionate objectives Therefore, mathematical models become more realistic if distinct evaluation aspects are explicitly considered as objective functions rather than being encompassed by a single economic indicator [9]. And, planning must take due consideration of the restrictions and must develop concepts and structures which are technically and economically sound [11].

In this section the model is described mathematically. The decision variables, constraints and objective functions are discussed.

There are several factors to be considered in power generation expansion planning. Economics, socio-cultures, institutional policies, environmental impacts, technology and space are factors to be taken into account in expansion planning decision [6]. These factors are influencing directly and indirectly on energy demand, supply and consumption in any nation.

One of the economic advantages of one country’s electricity market is to minimize the total operating costs by making the best use of national resources, i.e. by dispatching the least expensive generator with the constraint of maximum interconnection capacity in the nation [7]. This entails that it is better to reduce energy imported and to increase exported energy. In

Ethiopia at the moment, no energy is exported rather significant energy source (petroleum products) is imported- covering about 5% of the total energy balance.

Among them, one can focus on economics (investment and generation cost), environmental impacts, carbon trading and energy imported.

Definitions:

Some terms that are utilized in mathematical modeling are described first.

$\sum_{i \in N} p_i$: sum of p_i over all elements i in the set N

Generation: Electric power generation

Demand: Electric power demand

Carbon trade: A transaction on the issue of global warming in which Ethiopia can capture carbon emissions released by other countries.

Elements: The main elements of any constrained optimization problem are objective function, variables, constraints and variable bounds.

Objective function: This is a mathematical expression that combines the variables to express our goal. It may represent profit and/ or cost. We will be required to either maximize or minimize the objective function.

Variables (also called decision variables): The values of the variables are not known when we start the problem. They usually represent things that we can adjust or control. The goal is to find values of the variables that provide the best value of the objective function.

Constraints: These are mathematical expressions that combine the variables to express limits on the possible solutions.

Variable bounds: Only rarely are the variables in an optimization problem permitted to take on any value from minus infinity to plus infinity. Instead the variables usually bounds.

Indices

p ε M--types of generation units

p: is an index starting at 1 and ending at M

M: number of power plants having been considered

k ε F--types of fuel

k: is an index staring at 1 and ending at F

F: number of fuel power plants having been considered

3.2.4.1. Objective Functions

In this model, the minimization of the investment and generation cost, environmental impact, cost of imported fuel and maximization of carbon trade revenue of the whole system are considered.

i. Investment and Generation Cost:

Investment cost is due to total cost for building the power plants. It is approximately proportional to MW generated [15].

Generation cost is the total annual cost incurred in power generation. It has three parts consisting fixed cost, semi-fixed and running cost. Fixed cost is independent of the capacity. It is due to cost of central organization, interest on the capital cost of land and salaries of higher officials and management. Semi-fixed cost is due to cost of interest and depreciation on the capital cost of generating unit and transmission network, insurance and compensation. It is approximately proportional to MW generated. Operating (running) cost is due to annual cost of fuel, lubricating oil, water, maintenance and repairing cost of equipments, and wages and salaries of operation, maintenance and supervisory staff. This cost is approximately proportional to energy generated (MWh) [9, 15].

Therefore, investment and generation cost can be formulated by adding the investment cost of new generating units and generating cost of existing and new units. Investment unit cost should be put into \$/MWh by using suitable equivalent converting factor so that the coefficients of objective function formulated should have the same units as far as the variables talk about identical unit.

$$f_1 = \begin{pmatrix} Investment\ cost\ for \\ new\ generating\ units \end{pmatrix} + \begin{pmatrix} Generation\ cost\ for\ \text{both} \\ \text{existing and new units} \end{pmatrix}$$

$$f1 = \begin{array}{c} \left(\text{Investment unt cost } \left(\frac{\$}{\text{MWh}}\right) \text{ of plants}\right) * (\text{generation (MWh) from new units}) \\ + \left(\text{Generation unit cost} \left(\frac{\$}{\text{MWh}}\right) \text{of plants}\right) * (\text{Generation (MWh)from both existing and new units}) \end{array}$$

The cost is influenced by the type of generating unit and its capacity. Thus, considering each type of plant contributing supply, we can develop the following objective function.

$$f_1 = \sum_{p=1}^{M} I_p gn_p \quad + \sum_{p=1}^{M} G_p(ge_p + gn_p) \tag{20}$$

where,

I_p-------Investment cost (\$/MWh) of a power plant p

gn_p-----Generation (MWh) from the new power plant p

G_p-------Generation cost (\$/MWh) of a power plant p

ge_p-----Generation (MWh) from the existing power plant p

This objective seeks the possible minimization of cost for investment and operation of generation expansion activities.

ii. Environmental impact:

This issue contains the emissions of greenhouse gases, social impacts, impact on wild life, air pollution, aesthetic, and land management.

But this paper focuses only on emissions. The major emissions include carbon dioxide, nitrogen oxide, sulfur dioxide and particulate matter. Carbon dioxide which is to be considered in the formulation of the following objective function is the dominant emission. The amount can be determined as the mass of emission released during the production of electricity in the plants.

Thus,

$$f_2 = [^{\text{Tons of CO}_2 \text{ emission per MW h}}_{\text{generated by units}}] * [\text{generation (MWh)from the units}]$$

Like in the first objective function, the emission is considered for each type of unit.

$$f_2 = \sum_{p=1}^{M} E_p[ge_p + gn_p] \tag{21}$$

where,

E_p------Tons of carbon dioxide emission per MWh generated by a unit of type p

gn_p-----Generation (MWh) from the new power plant p

ge_p-----Generation (MWh) from the existing power plant p

This objective tries to find the potential reduction of emission of carbon dioxide under expansion decision.

iii. Cost of imported fuel:

It can be determined multiplying unit cost of imported fuel by amount of imported fuel (taking corresponding unit). The fuel can be coal, oil or natural gas.

Thus,

$$f_3 = \left[\begin{matrix}\text{Unit cost}\left(\frac{\$}{\text{unit}}\right)\text{of} \\ \text{imported fuel}\end{matrix}\right] * [\text{imported fuel (in corresponding units)of type k}]$$

$$f_3 = \sum_{k=1}^{F} V_k u_k \tag{21}$$

where,

V_k-----Cost ($/MWh) of imported fuel of type k

u_k-----Imported fuel of type k

Making lowest to the possible degree of the amount of cost of imported fuel for power plants is granted by the objective function.

iv. Carbon Trade Revenue:

It is the benefit to the nation if the nation can capture carbon dioxide emission released by any other country to the atmosphere. This process is achieved by the plants in Ethiopia. But, in Ethiopia, bulky plants are cut down for satisfying energy consumption.

An amount of the revenue can be determined by evaluating the plants which can be equivalent to the MWh electrical energy produced by generating units**,** and by finding out the estimated hectare coverage or ton of plants which are corresponding to energy supply.

The average plants are about 1,100 stems per hectare or 8 tones of plants per hectare [24].A common hardwood has an energy content of 4.5 kWh per kilo gram[25]. The efficiency of wood stoves is in the range of 16 % (old) to 75 %(more modern)[26]. Considering the efficiency of

[24] *www.fao.org*
-The human and livelihoods cost of fuel-switching in Addis Ababa, Melessaw Shanko1 and Jonathan Rouse, Megan Power, P.O. Box 180884, Addis Ababa, Ethiopia. Email: j.r.rouse@gmail.com, Boiling Point, No 15-2005
-PROJECT DESIGN DOCUMENT FORM FOR AFFORESTATION AND REFORESTATION PROJECT ACTIVITIES -UNFCCC/CCNUCC- Version 04
[25] *http://en.wikipedia.org has referred the Sustainable Energy Development Office (SEDO), part of the Government of Western Australia*
[26] *www.frugal-living-freedom.com*
-www.bioenergylists.org

wood stove 16% (because in Ethiopia wood fuel is consumed traditionally), the useful energy becomes 0.72 MWh per ton of wood.

Let TT ($/tonne) be the average annual amount of revenue gained by carbon trade due to plants (in tones or hectare) preserved or afforested. This amount can be determined from the Humbo project. The Humbo Assisted Natural Regeneration Project was developed by World Vision in partnership with the World Bank to restore 2,728 hectares of natural forest in the vicinity of the town of Humbo in southwestern Ethiopia 40 km south of Sodo town. It is Ethiopia's first Clean Development Mechanism (CDM) project large-scale afforestation/reforestation (A/R) project registered under the United Nations Frame Convention on Climate Change (UNFCCC). It is expected to sequester over 880,000 metric tonnes of CO2e over 30 years[27]. It is annually an average of 29,333 metric tonnes of CO_2e is sequestered. It is provided to generate an income of $6 from 1 tonne of CO_2e sequestered[28].

From the Humbo project, tones of plants to be preserved,

$$= 2{,}728\ hectares * 8\,\frac{tones}{hectare}$$

$$= 21{,}824\ tones\ of\ plants$$

From the project, the annual revenue to be obtained is $0.167 million .

So, $TT(\frac{\$}{tone}) = \frac{0.167*10^6}{21{,}824}$ = $8.06/tonne of plants.

EE (MWh/tone) be amount of energy obtained from a tone of plants. The useful energy of common wood has 0.72MWh/tone.

Therefore, $R_p\left(\$/_{MWh}\right) = \frac{TT(\$/_{tone})}{EE(^{MWh}/_{tone})}$ amount of revenue (in USD) is obtained.

[27] *Ethiopia: Humbo Assisted Regeneration,(BioCarbon Fund), UNFCCC Reference No.: 2712*
[28] *Interview with the expert of Ethiopian Environmental Protection Authority*

Thus, $R_p\left({}^{\$}/_{MWh}\right) = \frac{TT({}^{\$}/_{tone})}{EE({}^{MWh}/_{tone})} = \frac{8.06}{0.72} = {}^{\$11.2}/_{MWh}$

Replacing the woody fuel consumption by electricity gives $11.2 from one MWh electric energy generated from power plants to be newly constructed.

$$f_{44} = \left[\begin{matrix}\text{Unit revenue}\left(\frac{\$}{\text{MWh}}\right)\text{from carbon trade} \\ \text{due to MWh generated by units}\end{matrix}\right] * [\text{generation (MWh)from new units}]$$

$$f_{44} = \sum_{p\epsilon M} R_p gn_p \qquad (22)$$

where,

R_p-----Revenue ($/MWh) from carbon trade achieved through MW generated by a power plant p

gn_p-----Generation (MWh) from the new power plant p

This objective is to maximize the revenue obtained from the carbon trading due to plants preserved in case of new power generation plants.

The maximization function f can be converted to minimization function multiplying by -1. So, equation (22) is written as

$$f_4 = -f_{44} = -\sum_{p\epsilon M} R_p gn_p \qquad (23)$$

These four objective functions need a way for solving the problem easily. On this base, the first, third and fourth objective problems are expressing the cost. These objective functions, therefore, come together, and it is as follows.

$$f_{134} = f_1 + f_3 + f_4$$

$$f_{134} = \sum_{p=1}^{M} I_p gn_p + \sum_{p=1}^{M} G_p(ge_p + gn_p) + \sum_{k=1}^{F} V_k u_k - \sum_{p=1}^{M} R_p gn_p \qquad (24)$$

Now the objective functions are reduced to two-namely environmental impact and cost functions.

Secondly, it is fundamental to look through the existence of variables in each objective problem as far as the two objective problems are not merged. Each objective problem in this thesis model has the decision variables appearing in other objective problems. For example, the decision variables of unit generations new (gn_p) and existing (ge_p) appear in equations (21) and (24). Solving these problems with imposed constraints can result in two different values in each same decision variable. At this time, it is difficult to decide the possible solution.

If one of these variables appears in two objective functions, it is important to develop technical solution way of resolving the problem. If none of the variable appears in different objective functions and in constraints, the variables are independent and to be solved individually. However, same variables exist in equations (21) and (24). Therefore, equations (21) and (24) are solved dependently by applying relevant solution technique.

However, if both [equations (21) and (24)] objective problems can be formulated in the same functions without missing any idea and minimizing accuracy, this is one way of solution technique. On this base, environmental impact problem is converted to cost-equivalent function problem by using some parameters. Carbon dioxide emission from the usage of electric power plants can cost that country and the size of cost is determined by depending on the amount of released emission to the atmosphere.

As it is done in the carbon trade sub model, emissions of carbon dioxide affecting the environment can be related with the cost. As explained above, while capturing 1 tone of CO_2 giving a benefit of \$6, emitting the same tone of CO_2 from the power system results in a loss of \$6. Therefore, equation (21) can be reformulated as follows.

Let CC_p(\$6/tone of CO_2) be cost factor

Multiplying the cost factor by emission factor E_p(tones of CO_2/MWh) gives cost emission factor(CE_p).

$$CE_p = \left(\begin{matrix} (USD\ cost\ per\ tone\ of\ CO_2\ emitted\ from\ power\ plants) * \\ (tones\ of\ CO_2\ emitted\ due\ to\ MWh\ generated\ from\ power\ plants) \end{matrix} \right) * (MWH)$$

$$CE_p = \left(\$6 / _{tone\ of\ CO_2} \right) * E_p \left(tones\ of\ CO_2 / _{MWH} \right)$$

$$f_2 = \sum_{p=1}^{M} CE_p [ge_p + gn_p] \qquad (25)$$

where,

CE_p-----Emission cost (\$/MWh) by a generating unit of type p.

Now, the objective functions can be combined to single objective function and it is as under.

$$f_{1234} = f_1 + f_2 + f_3 + f_4$$

$$f = f_{1234} = \sum_{p=1}^{M} I_p gn_p + \sum_{p=1}^{M} G_p (ge_p + gn_p) + \sum_{k=1}^{F} V_k u_k - \sum_{p=1}^{M} R_p gn_p + \sum_{p=1}^{M} CE_p [ge_p + gn_p]$$

Rearranging the similar terms, the following equation is developed.

$$\boldsymbol{f = \sum_{pe=1}^{m} (G_p + CE_p) ge_p) + \sum_{pn=m+1}^{M} (I_p + G_p + CE_p - R_p) gn_p + \sum_{k=1}^{F} V_k u_k} \qquad (\boldsymbol{26a})$$

The model of equation 26a is developed for the scenario-1. For scenario-2, the sub model of carbon trade is omitted and the following model of objective function is used.

$$\boldsymbol{f = \sum_{pe=1}^{m} (G_p + CE_p) ge_p) + \sum_{pn=m+1}^{M} (I_p + G_p + CE_p) gn_p + \sum_{k=1}^{F} V_k u_k} \qquad (\boldsymbol{26b})$$

3.2.4.2. Constraints

In the proposed model there are four types of constraints imposed in the system: power balance constraints in the network, generation capacity, amount of available local fuel, and non-negativity of the decision variables.

i. **Power balance equation**:

According to energy conservation, the total power generation from the plants is equal to sum of power consumed and lost.

In this thesis work, sum of power consumed and lost is referred to be demand

$$\sum_{p=1}^{M}[ge_p + gn_p] = D \tag{27}$$

where,

gn_p-----Generation (MWh) from the new power plant p

ge_p-----Generation (MWh) from existing power plant p

D -----Expected load or demand (MWh) at year t

ii. **Generation capacity for each unit type p** :

Operating limits are imposed by the generation units.

$$ge_p \leq GE_p \tag{28}$$

$$gn_p \leq GN_p \, ; p \leq M \tag{29}$$

where,

gn_p-----Generation (MWh) from the new power plant p

ge_p-----Generation (MWh) from existing power plant p

GN_p----- Maximum (MWh) generation capacity of a power plant p

GE_p-----Maximum (MWh) generation capacity for existing power plant p

iii. **Fuel demand for each fuel type k**:

Fuel used will be either from imported or if necessary from local markets.

$$\sum_{p=1}^{M} \boldsymbol{W_p(ge_p + gn_p) \leq U_k + u_k; k \in F} \qquad (30)$$

where,

W_p-----Fuel needed (Units/MWh) to operate a power plant p

gn_p-----Generation (MWh) from the new power plant p

ge_p-----Generation (MWh) from existing power plant p

U_k-----National available amount (corresponding unit) of fuel type k

u_k-----Imported fuel of type k

Investment and generation unit costs of a unit of type p, I_p G_p, (\$/MWh); CO_2 unit emission by a unit of type p, E_p(ton/MWh); revenue, R_p, (\$/MWh) from carbon trade due to MWh generated by a unit of type p; maximum generation capacity (MWh) of existing , GE_p, and new, GM_p ,units of type p; fuel needed, W_p, (units /MWh) to operate a unit of type p; and national available amount, U_k, of fuel type k are tabulated in *Appendix A, Table A1*.

iv. **Non-negativity**:

No negative values are permitted for the decision variables

$$\boldsymbol{ge_p, gn_p, u_k \geq 0, \forall p, k} \qquad (31)$$

gn_p-----Generation (MWh) from the new power plant p

ge_p-----Generation (MWh) from existing power plant p

u_k-----Imported fuel (corresponding units) of type k

General Model:

Let $f(x)$ be objective function (32)

$$x = (ge, gn, u)$$

$$\mathrm{x} \in \mathrm{X} = \text{feasible solution space}$$

The general model has $|M| + |F|$ variables and $3 + |F|$ constraints.

3.2.5. Solution Technique

Optimization techniques are used to find a set of design parameters, $x = \{x_1, x_2, ..., x_n\}$, that can in some way be defined as optimal. In a simple case this might be the minimization or maximization of some system characteristic that is dependent on x. In a more advanced formulation the objective function, $f(x)$, to be minimized or maximized, might be subject to constraints in the form of equality constraints, $G_i(x) = 0$ ($i = 1, ..., m_e$); inequality constraints, $G_i(x) \leq 0$ ($i = m_e + 1, ..., m$); and/or parameter bounds, x_l, x_u.

where x is the vector of length n design parameters, $f(x)$ is the objective function, which returns a scalar value, and the vector function $G(x)$ returns a vector of length m containing the values of the equality and inequality constraints evaluated at x.

Practical optimization is the art and science of allocating scarce resources to the best possible effect. Optimization techniques are called into play every day in questions of industrial planning, resources allocation, scheduling, decision-making, etc. A maximum profit or a minimum cost and/or both optimization models are used accordingly to solve the aroused problems [22].

There are classical and numerical methods of optimization [21]. The two common of the numerical type methods of optimization problems are linear and nonlinear models.

Linear programming studies the case in which the objective function *f* which is to be minimized or maximized and is linear and the set of the design variable space is specified using only linear equalities and inequalities[20,21].

Nonlinear programming is identical to linear programming except that the relationships can have a nonlinear form. It studies the general case in which the objective function or the constraints or both contain nonlinear parts [20, 21].

In this thesis the developed mathematical models are in linear forms. Therefore, the problems are to be resolved by applying linear programming method.

3.2.5.1. Algorithm

There are three types of algorithm in linear programming including medium-scale simplex, active set medium-scale and large-scale linear programming algorithms. Among them simplex algorithm is implemented in this thesis work because of efficient in moving basic solutions to construct the minimum. The simplex method is a step-by-step procedure for moving from corner point to corner point of the feasible solution space in such a manner that successively larger (or smaller) values of the maximization (or minimization) objective function are obtained at each step. The procedure is guaranteed to yield the optimal solution in a finite number of steps [23].

Medium-Scale Linear Programming Simplex Algorithm

The basic algorithm most often used to solve linear programming problems is called the *simplex method*. Over the past years, it has been developed to the point that good computer programs using the simplex method and it can solve virtually any bounded, feasible linear programming problem of reasonable size in a reasonable amount of time [20]. The simplex algorithm, invented by George Dantzig in 1947, is one of the earliest and best known optimization algorithms. The algorithm solves the linear programming problem.

The problems of equations from (26) to (31) have the form of equivalent LP software model as equation (33).

$$\boldsymbol{min\ \ f^{T}(x)\ \ such\ that} \begin{cases} \boldsymbol{A.x \le b} \\ \boldsymbol{A_{eq}\,.x = b_{eq}} \\ \boldsymbol{lb \le x \le ub} \end{cases} \tag{33}$$

where *x* is the vector of length *n* design parameters-decision variables(ge, gn, u), *f*(*x*) is the objective function, which returns a scalar value, and the vector function A(*x*) returns a vector of length *m* containing the values of the equality and inequality constraints evaluated at *x;* and *lb* and *ub* are the vectors of lower and upper bounds respectively of decision variables.

The objective function can be written as

$$f(x)=C_1x_1+C_2x_2+\ldots.+C_nx_n \tag{34}$$

In matrix form, equation (34) is written as

$$f(x)=\mathbf{C^{T}X} \tag{35}$$

where,

C_1, C_2, ….,C_n are constants and x_1, x_2, …,x_n are decision variables.

Equation (33) is the matrix form of the models shown in equations (26), (27), (28), (29),(30), and (32).

The coefficients of the models or the elements of the matrices are organized as shown in Table 12.

Table 12: The organization of parameters used in the model which can fit with the matrix of LP software model in a corresponding power plants

p	Plant	Annual Energy(MWh) (ub_p)	Investment cost(Ip)	Generation cost(Gp)	Cost-Emission factor(CEp)	unit revenue(Rp)	fuel unit cost(Vk)	unit fuel required (Wp)	Coefficients of objective function (C_i) (Ip+Gp+CEp-Rp+Vk)
			$/kW	$/MWh	$/MWh	$/MWh	$/unit	unit/MWh	
1	Koka	61000	0	15	0.129	0	0	0.00	15.129
2	Tis Abay I	35000	0	15	0.129	0	0	0.00	15.129
3	Awash II	140000	0	15	0.129	0	0	0.00	15.129
4	Awash III	140000	0	15	0.129	0	0	0.00	15.129
5	Fincha	704000	0	15	0.129	0	0	0.00	15.129
6	Melkawakana	503000	0	15	0.129	0	0	0.00	15.129
7	Altu Langano	17000	0	12	0.531	0	0	0.00	15.531
8	Tis Abay II	169000	0	15	0.129	0	0	0.00	15.129
9	Gilgel Gibe I	822000	0	15	0.129	0	0	0.00	15.129
10	Diesel plants	568000.0	0	75	3.6	0	0.81	265.00	78.6
11	Tekeze	1043000	0	54	0.129	0	0	0.00	54.129
12	Gilgel Gibe II	1912000	0	54	0.129	0	0	0.00	54.129
13	Tana Beles	1364000	0	54	0.129	0	0	0.00	54.129
14	Adama 1 Wind	161,000	238	55.8	0.129	-11.2	0	0.00	282.729
15	Ashegoda Wind Park	197,370	456	55.8	0.129	-11.2	0	0.00	500.729
16	Messobo Wind Park	103,700	984	55.8	0.129	-11.2	0	0.00	1028.729
17	Ayisha wind Park	592,370	506	55.8	0.129	-11.2	0	0.00	550.729
18	Amertinesh	215,000	451	54	0.129	-11.2	0	0.00	493.929
19	GilgelGibeIII	5,300,000	176	54	0.129	-11.2	0	0.00	218.929
20	D/ Birhan wind Park	197,370	760	55.8	0.129	-11.2	0	0.00	804.729
21	Asela wind Park	197,370	760	55.8	0.129	-11.2	0	0.00	804.729
22	Adama II wind Park	161,000	634	55.8	0.129	-11.2	0	0.00	678.729
23	Genale Dawa III	1,600,000	213	54	0.129	-11.2	0	0.00	255.929
24	Genale Dawa VI	1,475,000	242	54	0.129	-11.2	0	0.00	284.929
25	Chemoga Yeda I	780,000	332	54	0.129	-11.2	0	0.00	374.929
26	Chemoga Yeda II	568,000	386	54	0.129	-11.2	0	0.00	428.929
27	Geba I	935,000	338	54	0.129	-11.2	0	0.00	380.929
28	Geba II	852,000	306	54	0.129	-11.2		0.00	348.929
29	Halele Warabesa-1	460,000	443	54	0.129	-11.2	0	0.00	485.929
30	Halele Warabessa-2	1,570,000	251	54	0.129	-11.2	0	0.00	293.929
31	Millennium Dam	15,177,000	316	54	0.129	-11.2	0	0.00	358.929
32	Aluto Langano II	522,000	469	100	0.531	-11.2	0	0.00	558.331
33	Tekeze II	1,730,000	364	54	0.129	-11.2	0	0.00	406.929
34	Beko Abo	8,600,000	177	54	0.129	-11.2	0	0.00	219.929
35	Border	6,000,000	200	54	0.129	-11.2	0	0.00	242.929
36	Gibe 5TH	1,957,000	405	54	0.129	-11.2	0	0.00	447.929
37	Wabi Shebele	460,000	322	54	0.129	-11.2	0	0.00	364.929
38	Birbir	2,726,000	240	54	0.129	-11.2	0	0.00	282.929
39	Lower Dedessa	3,208,000	229	54	0.129	-11.2	0	0.00	271.929
40	Dabus	2,036,000	292	54	0.129	-11.2	0	0.00	334.929
41	Tams	5,892,000	170	54	0.129	-11.2	0	0.00	212.929
42	Genale Dawa 5th	655,000	229	54	0.129	-11.2	0.531	0.00	271.929
43	Gibe IV	5,930,000	236	54	0.129	-11.2	0.531	0.00	278.929
44	Gojeb	364,000	618	54	0.129	-11.2	0	0.00	660.929
45	Mendaya	11,194,000	161	54	0.531	-11.2	0	0.00	203.929
46	Tendaho	701,000	428	100	0.531	-11.2	0	0.00	517.331
47	Corbetti	526,000	463	100	0.531	-11.2	0	0.00	552.331
48	Abaya	701,000	428	100	0.531	-11.2	0	0.00	517.331
49	Tulu Moya l	280,000	500	100	0.531	-11.2	0	0.00	589.331
50	Dofan	420,000	500	100	0.531	-11.2	0	0.00	589.331
51	Yayu	596,000	294	47	5.205	-11.2	32	0.18	335.005
52	Imported oil	0	0	0	0	0	0	0	0.81
53	Imported coal	0	0	0	0	0	0	0	32.28

The inequality constraint is a 2 X 53 matrix. The number of rows indicates the types of fuel power plants considered. In this case, two types of fuel plants (oil and coal power plants) have been considered. The matrix elements of inequality constraint is taken from the Table 12 of the values of unit fuel required (Wp) in a corresponding power plants.

Main Algorithm

The simplex algorithm has two phases:

Phase 1(Start-up) — Compute an initial basic feasible point. That is, finding any cornerpoint feasible solution. The reason why we start our study of linear programming with standard form linear programmings is that the origin (the (0,0,…,0) point) is always a cornerpoint feasible solution in a standard form LP, so phase 1 is simple

Phase 2(Iterate) — Compute the optimal solution to the original problem. That is, repeatedly moving to a better adjacent cornerpoint feasible solution until no further better adjacent cornerpoint feasible solution can be found. This final cornerpoint feasible solution defines optimum point. Note that there could be other adjacent cornerpoint feasible solutions with the same optimum value.

In phase 2, the algorithm applies the simplex algorithm, starting at the initial point from phase 1, to solve the original problem. At each iteration, the algorithm tests the optimality condition and stops if the current solution is optimal. If the current solution is not optimal, the algorithm

1. Chooses one variable, the *entering variable*, from the nonbasic variables and adds the corresponding column of the nonbasis to the basis. Chooses a variable, the *leaving variable,* from the basic variables and removes the corresponding column from the basis.
2. Updates the current solution and the current objective value.

The call function of the solver is written as:

[x f exitflag output]=linprog(f,A,b,Aeq,beq,lb,ub,x0,options); that returns the value of objective function *f* at the solution *x*, value of *exitflag* that describes the exit condition, a structure *output* that contains information about the optimization. In other words, the input arguments and output arguments are:

Input arguments:

Problem f: Linear objective function vector f

A: Matrix for linear inequality constraints

b: Vector for linear inequality constraints

Aeq: Matrix for linear equality constraints

beq: Vector for linear equality constraints

lb: Vector of lower bounds

ub: Vector of upper bounds

x0: Initial point for x

solver: 'linprog'

Output arguments:

exitflag: Integer identifying the reason the algorithm terminated. The following lists are the values of exitflag and the corresponding reasons the algorithm terminated

1: Function converged to a solution x

0: Number of iterations exceeded maximum iteration (10 *number of decision variables)

-2: No feasible point was found

-3: Problem is unbounded

-5: Both primal and dual problems are infeasible *output:* Structure containing information about the optimization. The fields of the structure are:

iterations: Number of iterations

algorithm: Optimization algorithm used

message: Exit message

linprog returns empty output arguments for the decision variable x and value of objective function *f* if it detects infeasibility or unboundedness.

When the problem is unbounded, *linprog* returns x and *f* in the unbounded direction.

Duality: - Every linear programming problem where we seek to maximize the objective function gives rise to a related problem, called the *dual problem*, where we seek to minimize the objective function. The two problems interact in an interesting way: every feasible solution to one problem gives rise to a bound on the optimal solution in the other problem. If one problem has an optimal solution, so does the other problem and the two objective function values are the same. This is expressed by the following relationships.

$$\begin{array}{ccc} \min\ c^T x & & \max\ b^T y \\ Ax \le b & \leftrightarrow & Ay \le c \\ \begin{Bmatrix} n \quad variables \\ m\ constraints \end{Bmatrix} & & \begin{Bmatrix} m \quad variables \\ n\ constraints \end{Bmatrix} \end{array}$$

where,

c=the matrix of coefficients of objective function (primal problem) at n variables

b=vector of inequality constraints

A=matrix of inequality constraints (m x n matrix)

x= the vector of length *n* decision variables (primal problem)

y= the vector of length m dual variables in dual problem

Every linear programming problem falls into one of three categories:

1. **Infeasible**. A linear programming problem is infeasible if a feasible solution to the problem does not exist; that is, there is no vector x for which all the constraints of the problem are satisfied.
2. **Unbounded**. A linear programming problem is unbounded if the constraints do not sufficiently restrain the cost function so that for any given feasible solution, another feasible solution can be found that makes a further improvement to the function.
3. **Has an optimal solution**. Linear programming problems that are not infeasible or unbounded have an optimal solution; that is, the function has a unique minimum (or maximum) function value.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Results

The designed model in this thesis denoted by mathematical formulation is in the form of linear model. Thus, the linear programming is used here so as to overview the result. Linear programming model developed previously is now implemented in MATLAB software. The solver of LP Simplex Algorithm built in MATLAB is used.

A *built-in* function (solver) of linear programming is imbedded in the MATLAB environment. A MATLAB code (Appendix B) is written in M-file workspace.

The values of matrices of objective function, constraints and bounds are organized in Table 12. The elements of objective function are prepared from the investment unit cost, generation unit cost, cost emission factor, unit revenue of carbon trade and fuel unit cost. The matrix elements of equality constrain is the matrix of coefficients of generation and imported fuel-that is unit row matrix for generation and zero row matrix for imported fuel. The elements in inequality constraints are made up of the unit fuel required for fuel type power plants. The maximum capacity of power plants is taken as the elements of upper bound matrix. Based on the functions of the model and Table 12, software models (equation 33) are organized as follows.

For model-1;

```
f01=  [15    15    15    15     15     15    13    15    15    79      54    54
       54    283   501   1029   551    494   219   805   805   679     256   285
       375   429   381   349    486    294   354   558   407   220     243   448
       365   283   272   335    213    272   279   661   204   517     552   517
       589   589   335   0.81   32.28];

aa=   [0     0     0     0      0      0     0     0     0     265.00  0     0
       0     0     0     0      0      0     0     0     0     0       0     0
       0     0     0     0      0      0     0     0     0     0       0     0
       0     0     0     0      0      0     0     0     0     0       0     0
       0     0     0     -1     0];

bb=   [0 0   0     0     0      0      0     0     0     0     0       0     0
       0     0     0     0      0      0     0     0     0     0       0     0
       0     0     0     0      0      0     0     0     0     0       0     0
```

```
        0       0       0       0       0       0       0       0       0       0       0       0
        0       0.18    0       -1];

A=[a;b];

b=[0;110000];

Aeq= [1 1       1       1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1       1
        1       1       0       0];

beq1=[ 23525000];

lb=zeros(53,1);

ub=     [61000    35000   140000  140000  704000  503000  17000   169000  822000  568000  1043000

        1912000  1364000  161000  197370  103700  592370  215000  5300000  197370  197370  161000

        1600000  1475000  780000  568000  935000  852000  460000  1570000  15177000  522000  1730000

        8600000  6000000  1957000  460000  2726000  3208000  2036000  5892000  655000  5930000  364000

        11194000 701000  526000  701000  280000  420000  596000  141234  300000];
```

For model-2;

```
f02=    [15     15      15      15      15      15      13      15      15      79      54      54
        54      294     512     1040    562     505     230     816     816     690     267     296
        386     440     392     360     497     305     365     570     418     231     254     459
        376     294     283     346     224     283     290     672     215     529     564     529
        601     601     346     0.81    32.28];

beq1=[20073000];
```

The rest matrices are the same as that of model-1.

f01 and f02 stand for coefficients of objective functions for model-1 and model-2 respectively. A, Aeq,b, beq,lb and ub represent the matrix of inequality constraints, equality constraints, the vector of the right hand side of inequality constraints, the vector of equality constraints (annual demand), lower bunds of decision variables(zero matrix) and upper bounds of decision variables (maximum generation capacity of the power plants) respectively.

4.1.1. Result of model-1

Based on prepared MATLAB code, the result of the model executed in MATLAB linear programming solver is shown as under.

Warning: Simplex algorithm uses a built-in starting point; ignoring user-supplied x0.

> In linprog at 254

Minimize using simplex.

Iter	Objective	Dual Infeasibility
	f1'*x1	A'*y+z-w-f1
0	6.36539e+009	971.625
1	6.28139e+009	536.614
2	6.08472e+009	421.582
3	6.02907e+009	313.38
4	5.96994e+009	150.273
5	5.42684e+009	339.829
6	3.75374e+009	80.4114
7	3.75058e+009	107.033
8	3.74211e+009	6
9	3.71031e+009	0

Optimization terminated.

x1 =[x1’]

61000	35000	140000	140000	704000	503000	17000	169000	822000
0	1043000	1912000	1364000	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	5421000	0	0	0	11194000
0	0	0	0	0	0	0	0	

fopt1 =

3.7103e+009

exitflag =

1

output =

iterations: 9

algorithm: 'medium scale: simplex'

message: 'Optimization terminated.'

4.1.2. Result of model-2

In scenario 2, the model is ignoring the sub-model of carbon trade in the objective function. Implemented the developed model in MATLAB LP solver, the annual demand (MWh) and minimized cost is shown in the following figure.

Warning: Simplex algorithm uses a built-in starting point; ignoring user-supplied X0.

> In linprog at 254

Minimize using simplex.

Iter	Objective	Dual Infeasibility
	f2'*x2	A'*y+z-w-f2
0	5.70291e+009	311
1	5.50076e+009	485.254
2	5.07655e+009	372.492
3	3.39745e+009	340.955
4	3.11982e+009	0

Optimization terminated

x2 =[x2’]

61000	35000	140000	140000	704000	503000	17000	169000	822000
0	1043000	1912000	1364000	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	1969000	0	0	0	11194000
0	0	0	0	0	0	0	0	

fopt2 =

3.1198e+009

exitflag =

1

output =

iterations: 4

algorithm: 'medium scale: simplex'

message: 'Optimization terminated.'

Note: *y* and *w* in the displays of the results consist dual variables and *z* consists dual slacks. Slack variables are added to change the inequality constraints in to equality constraints. But they are not used for the decision of the system.

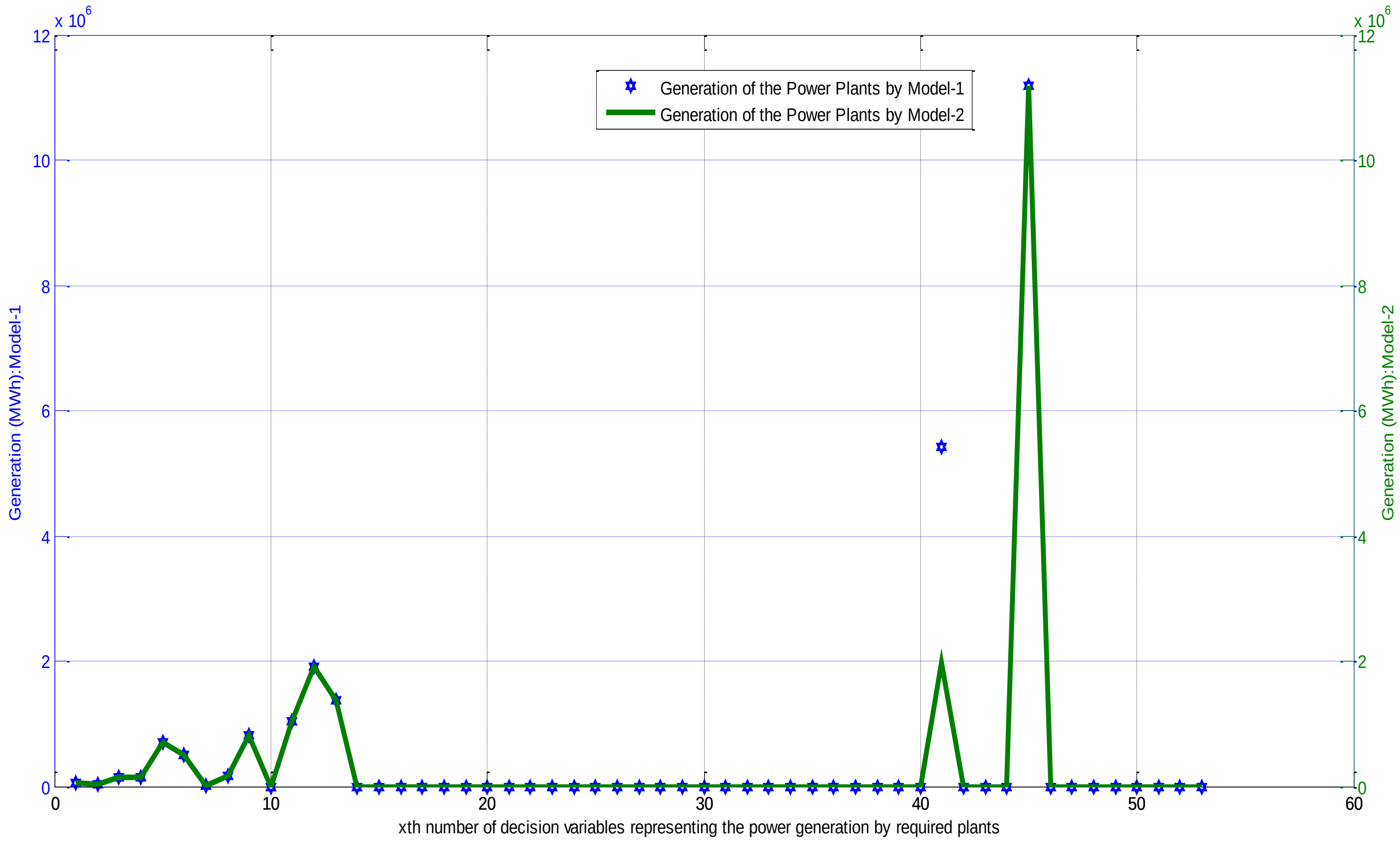
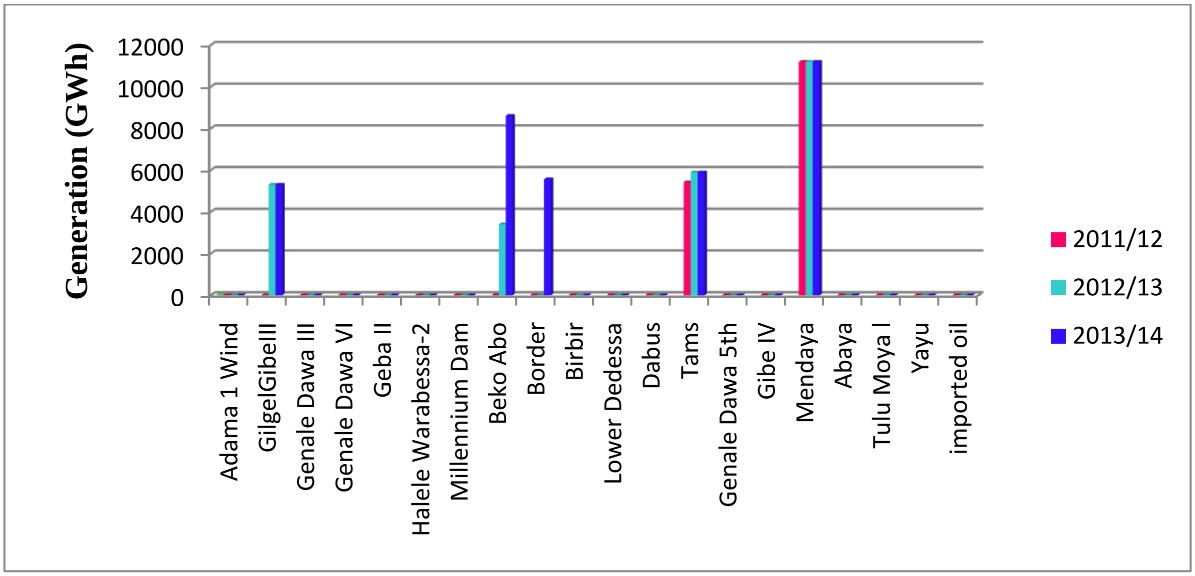
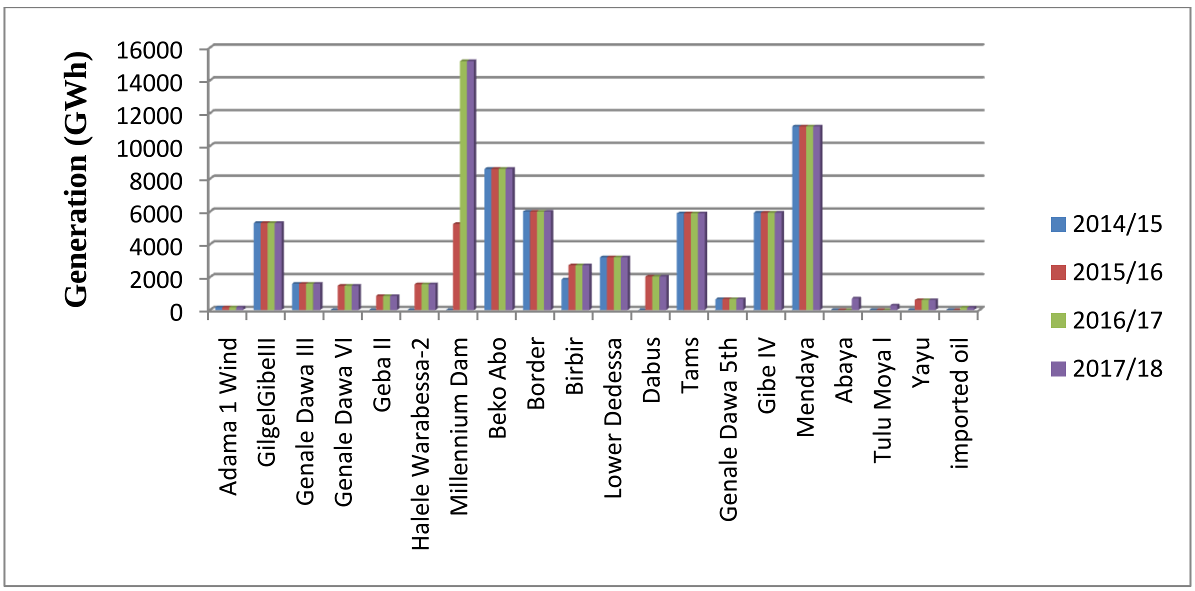


Figure 3: The result of model-1 and model-2 implemented in MATLAB solver for the year 2011/12

The solution of the model in scenario 1 and scenario 2 solved by MATLAB solver within the years 2011/12 and 2017/18 is shown in the chart-3 and chart-4 respectively. All detail information of the result is obtained in Appendix A, tables A5 and A6.

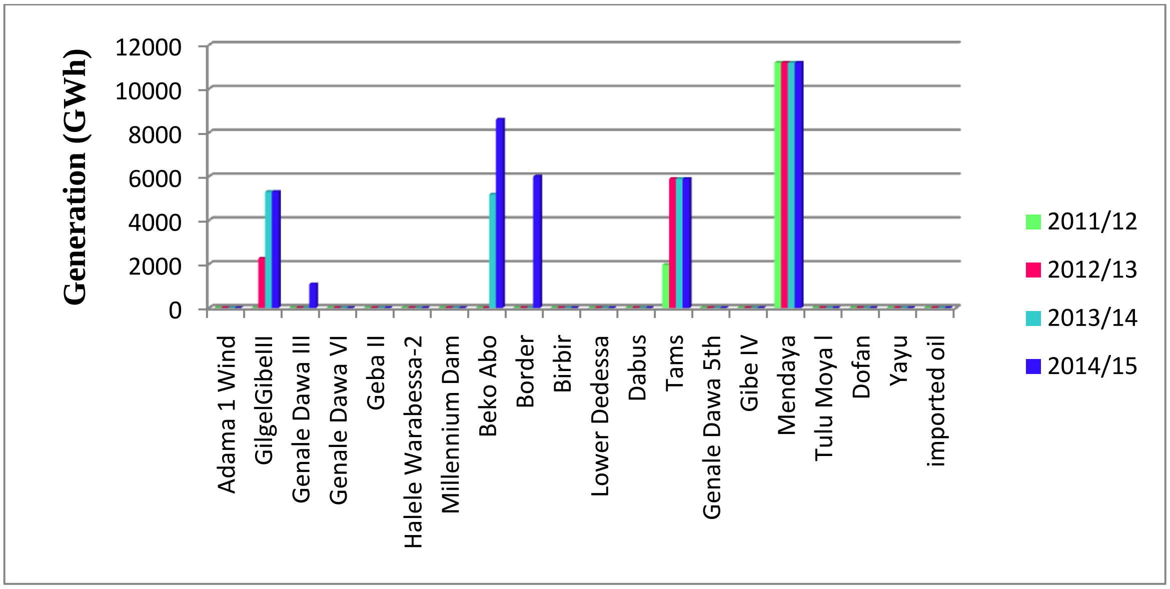


3a;

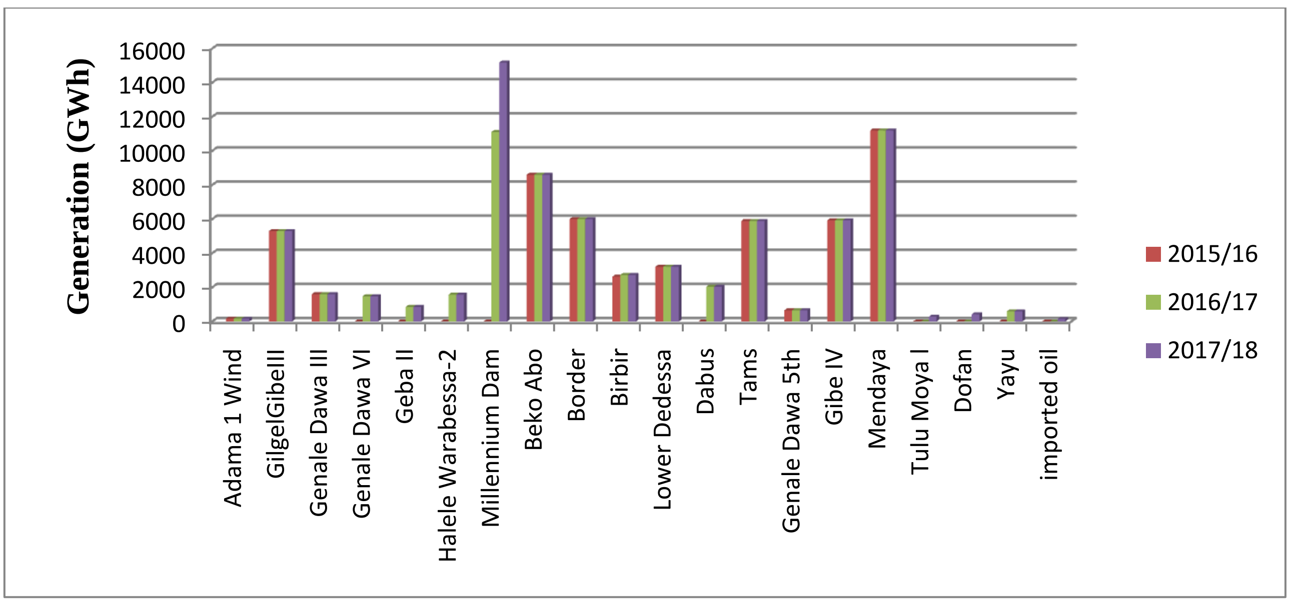


3b;

Chart 3a and 3b: The annual generation (GWh) of power plants to be added in the period 2011/12 to 2017/18 for model-1



4a;



4b

Chart 4a and 4b: The annual generation (GWh) of power plants to be added in the period 2011/12 to 2017/18 for model-2

4.2. Discussion

The result of the developed models is analyzed as follows. The models are implemented in the MATLAB linear models solver with prepared programming code.

a. Comparing the results of total cost in model-1 and model-2

Scenario 1

Table-13: Annual generation (GWh), total annual cost ($millions) and generation (GWh) from new power plants by model-1 implemented in the linear model solver of MATLAB

Year	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17
Total annual generation(GWh)	23,525	32,696	43,665	57,313	69,945	83,922
Total annual cost($millions)	3,710	2,995	3,925	5,635	6,596	8,073
Generation (GWh) from new plants	16,615	9,171	10,969	13,648	12,632	14,047

Scenario 2

Table-14: Annual generation (GWh), total annual cost ($millions) and generation (GWh) from new power plants by model-2 implemented in the linear model solver of MATLAB

Year	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17
Total annual generation(GWh)	20,073	26,258	34,473	44,980	58,086	75,811
Total annual cost($millions)	3,122	2,385	3,216	4,370	6,108	9,259
Generation (GWh) from new plants	13,163	6,185	8,215	10,507	13,106	17,725

It is usually true that as electricity generation to be produced is high, the cost for the production will be more. As seen in the figure 4 above, the annual demand in scenario 1 is more than the demand in scenario 2 in corresponding years. The total annual cost in model-1 is more than the cost in model-2 in all years except the year 2016/17. The comparison of annual generation and cost between model-1 and model-2 is shown in figure 8 and figure 9 respectively. But, it needs further investigation to be gone through so as to know the variation of the cost at the year 2016/17.

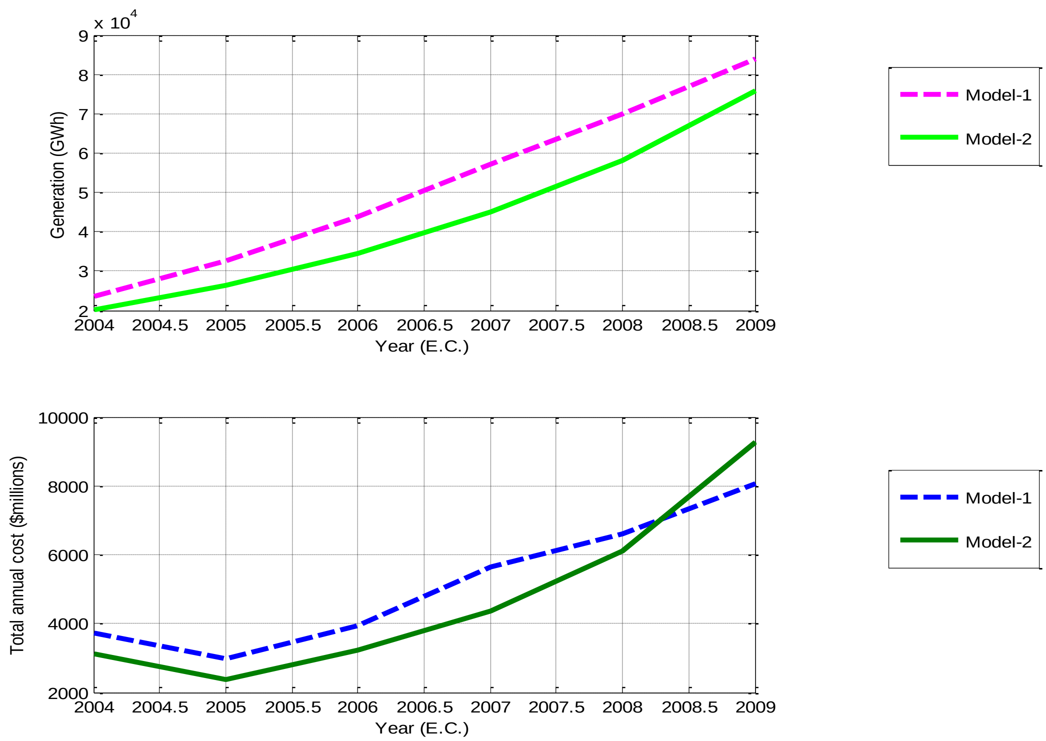


Figure 4: The comparison of annual generation between model-1 and model-2; and The optimized total annual cost comparison between model-1 and model-2 in the period of 2011/12 to 2016/17

Comparing the variation of the generation between the two models, there is significant gap at the year 2016/17 (Table 15).

Table 15: Generation from new plants and share of annual investment cost in model-1 and model-2

Year	**2011/12**	**2012/13**	**2013/14**	**2014/15**	**2015/16**	**2016/17**
Generation from new plants (GWh): model-1	16,615	9,171	10,969	13,648	12,632	14,047
Generation from new plants (GWh): model-2	13,163	6,185	8,215	10,507	13,106	17,725
Difference of new generation (%) between model-1 and model-2	21%	33%	25%	23%	-4%	-26%

From Table 15, the newly annual additional generation in model-1 is more for the first four years and less for the next years than that of in model-2. The investment cost shares mostly more than half (Appendix A, Table A5 and A6). The degree of the variation at the year 2015/16 is less. On this view, even though the additional generation in model-2 is slightly more than in model-1, the total annual generation at the year 2015/16 is much more in model-1. At the result the total annual cost in model-1 exceeds the model-2 at this year by some amount (Figure 4). But there is considerable difference of generation from new power plants at the year 2016/17. That is why the total cost of model-2 goes above the cost in model-1 at this year.

b. Comparing the results of the unit cost ($/MWh) between model-1 and modle-2

The total annual cost includes investment and generation costs. The average percentage of annual investment cost from the total annual cost is 56% for model-1 and 53% for model-2. It is also to look through the levelized cost[29] by comparing the results of this thesis work models. On this observation, the levelized cost of the result of the optimizing models is averagely $105/MWh for model-1 and $120/MWh for model-2 (Table 16). The levelized cost is dominated by the investment cost (Table 16). As the share of investment cost is high (that is more power plants constructed), the levelized cost becomes increased.

Table 16: Levelized cost in model-1 and model-2

Year		2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	Average
Levelized cost ($/MWh)	Model-1	158	92	90	98	94	96	**105**
	Model-2	156	91	93	97	105	122	**111**
Share of investment cost (%)	Model-1	73%	54%	53%	56%	55%	56%	**56%**
	Model-2	68%	45%	45%	47%	50%	57%	**53%**

[29] *Levelized cost is the present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments*

c. Cost due to additional generation

The additional generation in model-1 that goes beyond the generation in model-2 is shown in Table 17**.** This generation is planned due to the ambitious of delivering electricity all the urban households for their energy requirements. It needs extra cost. But the cost is very less compared to the cost spent on regular electricity generation (Table 17). The average investment unit cost used as raw data for models is $1,241/kW

Table 17: Extra cost due to extra generation in model-1 and unit cost ($/kW)

Year	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17
Extra cost in mode1-1($millions)	588	610	709	1,264	488	-1,186
Extra generation in model-1 (MW)	744	1,387	1,980	2,656	2,554	1,747
Unit cost ($/kW) due extra generation	791	440	358	476	191	

d. Revenue from the carbon trade

The revenue from the carbon transaction due to preserving of forest, afforestation and reforestation by switching off the wood and charcoal consumption into electricity is significant values in each year. It is tabulated in Table 18. This is the result of the model implemented for scenario-1.

Table-18: Annual revenue ($ millions) due to forests reserved in case of additional generation (GWh)

.Year	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17
Generation difference between two models (GWh)	3,452	6,438	9,192	12,333	11,859	8,111
Installed capacity (MW) @pf=53%	744	1,387	1,980	2,656	2,554	1,747
Annual revenue due to $11.2/MWh generation($millions)	38.66	72.11	102.95	138.13	132.82	90.84

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The electricity requirements have grown tremendously in Ethiopia and the demand has been running ahead of supply. The forecasted demand growth of electrical energy in Ethiopia becomes increased due to urbanization, growth and transformation plan, economic and social developments. The forecasted electrical energy demand done in this thesis in the country is increased averagely by 34.78% in scenario-1 and by 31.98% in scenario-2 yearly for the next 10 years. Comparing the forecasted demands by scenario-1 and scenario-2 with that of EEPCo plan are averagely differed by 32% and 27% respectively yearly.

The demand in each EEPCo tariff category of domestic, commercial, LV industry, HV industry, street lighting and own consumption will increase by 31.22%, 32.64%, 38%, 41.7%, 18% and10% respectively in scenario-1 and the same in scenario-2 except in domestic increased by 11.33%. It was the growth rate for each category 3.4%, 19%, 27%, 14%, 17.8% and 9.5% respectively for the last eight years. Comparing the last trends of electric production growth with the result of forecasted demand, growth rates of the industry, commercial and domestic subsectors make big difference. This is because:

- The industrialization plan and many factories are being constructed and needed huge electricity consumption.
- In domestic sub sector, the thesis work focuses on the switching off wood and charcoal consumption in urban areas and replaced by electricity.
- The economic growth plan by the government and considered by this thesis work is high (14.9%). The more income results in an increase of electricity demand by the customers of power utility.

The incorporation of carbon trade in electric power generation expansion planning can minimize the total cost by prominent amount and the investment cost can also be reduced due to revenue obtained from the trade cap. For the years of 2011/12 to 2015/16, due to consideration of carbon trade, from an average of 8,655 GWh generations per annum by new power plants, an average of 97 million USD annually is obtained regardless of other benefits like preserving the environment, minimizing the soil erosion, ensuring job opportunity of the surrounding community, nixing the domestic energy consumption of wood, charcoal and fuel in urban area, improving the life standard of the people, and function of electric energy in different economic sectors and public services. The investment and generation cost expended is an average of 0.0112 USD to produce a kWh electric energy in case of extra generation produced if carbon trade is included in generation expansion planning. It is very low compared to the cost of an average of 0.111 USD to produce a kWh electric energy by regular approach like model-2.

Oil fuel for power generation and cooking in urban areas come to nil in the periods in which the model is intended. This will minimize the fuel to be imported.

From the results of the models, the power generating plants having least unit cost ($/MWh) is considered first for the decision of generation expansion. Based on the result of the model, for example, Mendaya has least unit cost among the plants newly to be added, and it will all be exploited in the first planning year.

From the result, it has been shown that model-1 looks as if to be requiring higher cost. But, the investment unit cost for the extra generation in model-1 is highly reduced. And, model-1 needs lower levelized cost than in model-2. It is $105/MWh for model-1 and $111/MWh for model-2.

To satisfy the electricity requirement, to maximize the benefits from the environmental preservation and to minimize the fuel to be imported for power plants, the right generation planning has been done by this thesis. Model-1 is the better model for optimal power generation expansion planning.

5.2. Recommendation

The decisions to be taken during power generation expansion planning are;

1. The demand forecasting shall be made on the basis of updated information and the methods end-use and econometric analyses should be implemented so that the forecasted demand shall not exceed the real demand, because it adds unnecessary cost and the forecasted demand shall not be less than the real demand, because significant economy lose and declining of modern life of the people can be occurred from the power scarcity
2. Energy generation of the country shall need suitable composition so as to fix the energy balance by minimizing deforestation for energy consumption.
3. Incorporation of carbon trading in the decision of generation planning shall be better. It is benefiting the country on the bases of direct revenue from the trade cap, preserving the environment, minimizing the soil erosion resulting in GDP reduction, ensuring job opportunity of the surrounding community, nixing the domestic energy consumption of wood, charcoal and fuel in urban area, improving the life standard of the people.
4. This model shall be the reference and manual for the generation expansion in EEPCo planning decisions.

5.3. Future Work

A. The model can be modified by including transmission network system. The importance of considering the transmission network is to find generation expansion plan which can optimize more universally the electricity supply chain.

B. Evaluation of the economic and technical characteristics of the existing system of generating units and of the plants that are considered as potential units for system expansion is included. This adds more accuracy of the result to the model.

C. The method of the combination of end-use and econometric analyses will be included in demand forecasting. This also adds more accuracy of the result to the model.

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Appendix A

Table A1: investment cost ($/kW), operating cost ($/MWh), generation cost ($/MWh), CO_2 emissions (g/kWh) and capacity factor of different types of power plants.

Type	Investment Cost-I_p($/kW)	Operating Cost -Op($/MWh)	Generation cost -Gp($/MWh)	CO_2 emissions (kg/MWh)	Average cost due to emissions CE_p($/MWh)	Capacity factor (US Ave.)
Coal fired	1000-1500	17-30	51-76	755-980	5.205	68
Gas-fired	400-800	31-51	71-79	385-519	2.712	85
Diesel	600-800	30-60	60-90	400-800	3.600	82
Nuclear	1000-2700	9-15	71-83	6-130	0.408	90
wind	1000-2023	9-25	23-88	6-37	0.129	30
Hydro	890-2500	10-20	24-84	3-40	0.129	44
Biomass	1800-2000	40-60	51-77	29-82	0.333	68
PV	4000-5000	5-10	191-261	30-101	0.393	20
Geothermal	1432-4000	10-15	45-300	55-122	0.531	90

Source:

- *Paper presented at the 2ndSmall Hydropower For Today Conference IN-SHP, Hangzhou, China on 22-25 April, 2006; by Eng.JamesMuriithi; Ministry of Energy-Kenya*
- *-Diversity and security for the Ethiopian Power System, A preliminary assessment of risks and opportunities for the power sector, To be Published August 2009, Ethio Resource Group (ERG) for Heinrich Boll Foundation (HBF) and Forum for Environment (FfE)*
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- *Idaho national laboratory http://hydropower.inel.gov/hydrofacts/plant_costs.shtml*

Table A2: Average amount of fuel required to produce a unit of electricity in fuel power plants.

Type of fuel	Amount of fuel required to produce a unit of electricity
Coal	0.18 Tone/MWh[30]
Diesel	265.6 Liter/MWh
Natural gas	122 Gallons/MWh

[30] *EEPCO main report, January 2003*

Table A3: Fossil fuel price forecast and their unit cost in power generating plants

Year	Fuel Unit Price- V_k($/unit) Forecast[31] for Power Plants		
	Natural Gas ($/Gallon)	**Diesel Oil ($/Liter)**	**Coal ($/ton)**
2010/11	2.89	0.81	32.28
2011/12	3.18	0.84	33.89
2012/13	3.50	0.88	35.59
2013/14	3.85	0.91	37.37
2014/15	4.24	1.01	39.24
2015/16	4.66	1.10	41.20
2016/17	5.13	1.12	43.26
2017/18	5.64	1.14	45.42
2018/19	6.20	1.16	47.69
2019/20	6.83	1.18	50.07

Table A4: Power generating plants and status of EEPCo Interconnected System (ICS) with their generation capacity

S.No	Name of the plant	Type of the plant	plant capacity(MM)	Annual energy production(GWh)	Plant factor	In-service date(E.C)	Status of power plants
1	Koka	Hydro	43.2	61	29%	1953	Operational
2	Tis Abay I	Hydro	12	35	81%	1956	Operational
3	Awash II	Hydro	32	140	59%	1959	Operational
4	Awash III	Hydro	32	140	59%	1963	Operational
5	Fincha	Hydro	134	786	67%	1965/94	Operational
6	Melkawakana	Hydro	153	503	41%	1980	Operational
7	Altu Langano	Geothermal	7.3	42	65%	1991	Operational
8	Tis Abay II	Hydro	73	169	69%	1993	Operational
9	Gilgel Gibe I	Hydro	184	817	51%	1996	Operational
10	Awash 7killo	Diesel oil	28	202	83%	1995	Operational
11	Kaliti	Diesel oil	11.2	81	83%	1995	Operational
12	Dire Dawa	Diesel oil	40	280	80%	1995	Operational
13	Tekeze	Hydro	300	1,043	40%	2002	Operational
14	Gilgel Gibe II	Hydro	420	1,912	52%	2002	Operational
15	Tana Beles	Hydro	460	1,364	34%	2002	Operational
Total			**1,836**	**7,575**	**47%**		
16	Adama 1	Wind park	51	161	36%	2003	Committed
17	Ashegoda	Wind park	120	197	19%	2004	Committed
18	Messobo/Harena	Wind park	51	104	23%	2004	Committed
19	Ayisha	Wind park	300	592	23%	2004	Committed
20	Amertinesh	Hydro	97	215	25%	2005	Under construction
21	GilgelGibeIII	Hydro	1,870	5,300	32%	2005	Under construction
22	Debre Birhan	Wind park	100	197	22%	2005	Committed
23	Asela	Wind park	100	197	22%	2005	Committed
24	Adama II	Wind park	51	**161**	36%	2005	Committed
25	Genale Dawa III	Hydro	254	1,600	72%	2006	Committed
26	Genale Dawa VI	Hydro	246	1,475	68%	2007	Committed
27	Chemoga Yeda I	Hydro	162	780	55%	2007	Committed
28	Chemoga Yeda II	Hydro	118	568	55%	2007	Committed
29	Geba I	Hydro	215	935	50%	2007	Committed
30	Geba II	Hydro	157	852	62%	2007	Committed

[31]*Feasibility Study of Conversion of Diesel Power Plant to Natural Gas, Canadian Gas Services International* www.canadiangasservices.com *, AUGUST 23, 2010*

31	Halele Warabesa-1	Hydro	96	460	55%	2007	Committed
32	Halele Warabesa-2	Hydro	326	1,570	55%	2007	Committed
33	Millennium – 5000	Hydro	5,250	15,177	33%	2007	Committed
34	Aluto Langano II	Geothermal	70	522	85%	2007	Committed
Total			**11,470**	**38,638**	**39%**		
35	Tekeze II	Hydro	450	1,730	44%	Candidate	
36	Beko Abo	Hydro	1,600	8,600	61%	Candidate	
37	Border	Hydro	1,200	6,000	57%	Candidate	
38	Gibe 5TH	Hydro	660	1,957	34%	Candidate	
39	Wabi Shebele	Hydro	87	460	60%	Candidate	
40	Birbir	Hydro	467	2,726	67%	Candidate	
41	Lower Dedessa	Hydro	613	3,208	60%	Candidate	
42	Dabus	Hydro	425	2,036	55%	Candidate	
43	Tams	Hydro	1,000	5,892	67%	Candidate	
44	Genale Dawa 5th	Hydro	100	655	75%	Candidate	
45	Gibe IV	Hydro	1,472	5,930	46%	Candidate	
46	Gojeb	Hydro	150	364	28%	Candidate	
47	Mendaya	Hydro	2,000	11,194	64%	Candidate	
48	Tendaho	Geothermal	100	701	80%	Candidate	
49	Corbetti	Geothermal	75	526	80%	Candidate	
50	Abaya	Geothermal	100	701	80%	Candidate	
51	Tulu Moya l	Geothermal	40	280	80%	Candidate	
52	Dofan	Geothermal	60	420	80%	Candidate	
53	Yayu	Coal	100	596	68%	Candidate	
Total			**22,169**	**92,614**	**53%**		

Source: EEPCo's Growth and Transformation Plan

Table A5: The result of forecasted electricity demand in Ethiopia from 2003/04 to 2019/20 and by EEPCo tariff category in scenario-1

G.C.	**Demand by Domestic (GWh)**		**Demand by HV Industry (GWh)**		**Demand by LV Industry (GWh)**		**Demand by Commercial(GWh)**		**Demand by own consumption (GWh)**	**Demand by Public lighting (GWh)**	**Total Demand (GWh)**
	Without GDP	**Demand due to GDP**	**Without GDP**	**Demand due to GDP**	**Without GDP**	**Demand due to GDP**	**Without GDP**	**Demand due to GDP**			
2003/04	552	552	422	422	404	404	527	527	7	30	2,590
2004/05	673	673	480	480	489	489	616	616	7	36	3,070
2005/06	820	820	627	627	577	577	746	746	9	52	3,777
2006/07	971	971	774	774	848	848	926	926	9	52	4,777
2007/08	1,208	1,208	691	691	925	925	991	991	10	55	5,175
2008/09	1,441	1,441	857	857	1,175	1,333	1,189	1,334	11	65	6,725
2009/10	1,577	1,577	1226	1,226	1,622	1,839	1,510	1,695	12	77	7,962
2010/11	1,877	2,128	2,173	2,464	2,238	2,538	1,963	2,203	13	91	12,201
2011/12	11,379	13,345	2,944	3,339	3,088	3,502	2,592	2,909	14	107	23,525
2012/13	11,748	13,779	3,260	3,697	4,261	4,833	3,447	3,868	16	127	32,696
2013/14	12,129	14,225	4,033	4,574	5,881	6,669	4,584	5,144	17	150	43,465
2014/15	12,522	14,686	5,632	6,387	8,115	9,204	6,097	6,842	19	177	57,313
2015/16	12,927	15,161	8,299	9,412	11,199	12,701	8,109	9,100	21	208	69,945
2016/17	13,345	15,651	9,909	11,238	15,455	17,528	10,785	12,103	23	246	83,781
2017/18	13,775	16,155	11,645	13,207	21,328	24,188	14,345	16,098	25	290	101,614
2018/19	14,219	16,676	13,507	15,318	29,433	33,380	19,078	21,409	28	342	124,810
2019/20	14,677	17,213	15,495	17,573	40,617	46,064	25,374	28,475	31	404	155,239

Table A6: The result of forecasted electricity demand in Ethiopia from 2003/04 to 2019/20 and by EEPCo tariff category in scenario-2

G.C.	Demand by Domestic (GWh)		Demand by HV Industry (GWh)		Demand by LV Industry (GWh)		Demand by Commercial(GWh)		Demand by own consumption (GWh)	Demand by Public lighting (GWh)	Total Demand (GWh)
	Without GDP	Demand due to GDP	Without GDP	Demand due to GDP	Without GDP	Demand due to GDP	Without GDP	Demand due to GDP			
2003/04	552	552	422	422	404	404	527	527	7	30	2,590
2004/05	673	673	480	480	489	489	616	616	7	36	3,070
2005/06	820	820	627	627	577	577	746	746	9	52	3,777
2006/07	971	971	774	774	848	848	926	926	9	52	4,777
2007/08	1,208	1,208	691	691	925	925	991	991	10	55	5,175
2008/09	1,441	1,441	857	857	1,175	1,333	1,189	1,334	11	65	6,725
2009/10	1,577	1,577	1226	1,226	1,622	1,839	1,510	1,695	12	77	7,962
2010/11	1,877	2,128	2,173	2,464	2,238	2,538	1,963	2,203	13	91	12,201
2011/12	2,233	2,533	2,944	3,339	3,088	3,502	2,592	2,909	14	107	20,073
2012/13	2,657	3,014	3,260	3,697	4,261	4,833	3,447	3,868	16	127	26,258
2013/14	3,162	3,586	4,033	4,574	5,881	6,669	4,584	5,144	17	150	34,473
2014/15	3,589	4,070	5,632	6,387	8,115	9,204	6,097	6,842	19	177	44,980
2015/16	3,704	4,201	8,299	9,412	11,199	12,701	8,109	9,100	21	208	58,086
2016/17	3,823	4,335	9,909	11,238	15,455	17,528	10,785	12,103	23	246	75,811
2017/18	3,945	4,474	11,645	13,207	21,328	24,188	14,345	16,098	25	290	90,817
2018/19	4,071	4,617	13,507	15,318	29,433	33,380	19,078	21,409	28	342	115,104
2019/20	4,201	4,764	15,495	17,573	40,617	46,064	25,374	28,475	31	404	153,543

Table A7: The result of forecasted electricity demand in Ethiopia from 2003/04 to 2019/20 and consumption per capita considered for scenario-1

G.C.	Total population (Million)	Total Demand (D1) (in GWh)	Considering loss (D2=D1+loss rate*D1) (in GWh)	Consider reserve (D3=D2+reserve rate*D2) (in GWh)	Installed capacity (MW) @pf=53%	Consumption per capita (kWh/capita)
2003/04	67.71	3,958	4,591	2,590	886	39
2004/05	69.58	4,287	4,973	3,070	963	45
2005/06	71.52	4,763	5,525	3,777	1,069	54
2006/07	73.50	5,459	6,332	4,777	1,299	66
2007/08	75.41	5,616	6,515	5,175	1,532	70
2008/09	77.37	6,642	7,705	6,725	2,100	88
2009/10	79.38	7,992	9,271	7,962	3,817	159
2010/11	81.45	11,119	12,898	12,201	2,949	306
2011/12	83.56	23,216	26,931	23,525	6,347	400
2012/13	85.74	26,320	30,531	32,696	9,747	439
2013/14	87.97	30,780	35,705	43,465	12,771	496
2014/15	90.25	37,315	43,285	57,313	16,951	637
2015/16	92.60	46,603	54,059	69,945	20,688	755
2016/17	95.01	56,788	65,874	83,781	24,779	882
2017/18	97.48	69,963	81,157	101,614	30,054	1,042
2018/19	100.01	87,153	101,097	124,810	36,915	1,248
2019/20	102.61	109,759	127,320	155,239	45,915	1,513

Table A8: The comparison of forecasted demand among scenario-1, scenario-2 and EEPCo plan in Ethiopia from 2003/04 to 2019/20 in corresponding years

Year (G.C)	By this thesis work`				By EEPCo		Difference Between scenario-1 and EEPCo (%)	Difference Between scenario-2 and EEPCo (%)	Difference Between scenario-1 and scenario-2(%)
	Senario-1		Scenario-2						
	Electricity Generation (GWh)	Installed Capacity (MW)	Electricity Generation (GWh)	Installed Capacity (MW)	Electricity Generation (GWh)	Installed Capacity (MW)			
2003/04	2,590	886	2,590	886	2311	791	11%	11%	0%
2004/05	3,070	963	3,070	963	2589	812	16%	16%	0%
2005/06	3,777	1,069	3,777	1,069	2897	820	23%	23%	0%
2006/07	4,777	1,299	4,777	1,299	3321	903	30%	30%	0%
2007/08	5,175	1,532	5,175	1,532	3547	1,050	31%	31%	0%
2008/09	6,725	2,100	6,725	2,100	3728	1,164	45%	45%	0%
2009/10	7,962	3,817	7,962	3,817	4,101	1,966	48%	48%	0%
2010/11	12,201	2,949	12,201	2,949	8,195	1,981	33%	33%	0%
2011/12	23,525	6,347	20,073	5,416	9,088	2,452	61%	55%	15%
2012/13	32,696	9,747	26,258	7,828	15,159	4,519	54%	42%	20%
2013/14	43,465	12,771	34,473	10,129	16,759	4,924	61%	51%	21%
2014/15	57,313	16,951	44,980	13,304	39,098	11,564	32%	13%	22%
2015/16	69,945	20,688	58,086	17,180	50,163	14,837	28%	14%	17%
2016/17	83,781	24,779	75,811	22,422	64,359	19,035	23%	15%	10%
2017/18	101,614	30,054	90,817	26,861	82,572	24,422	19%	9%	11%
2018/19	124,810	36,915	115,104	34,044	105,940	31,334	15%	8%	8%
2019/20	155,239	45,915	153,543	45,413	135,921	40,201	12%	11%	1%
						Average difference	**32%**	**27%**	**7%**

Table A9: The result of model-1 in MATLAB LP solver with the annual generation (GWh) of each generating power plants, and the total annual cost in the years 2011/12 to 2017/18

Name of plant	Annual generation of each generating unit(GWh)						
	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
	MATLAB	MATLAB	MATLAB	MATLAB	MATLAB	MATLAB	MATLAB
Koka	61	61	61	61	61	61	61
Tis Abay I	35	35	35	35	35	35	35
Awash II	140	140	140	140	140	140	140
Awash III	140	140	140	140	140	140	140
Fincha	704	704	704	704	704	704	704
Melkawakana	503	503	503	503	503	503	503
Altu Langano	17	17	17	17	17	17	17
Tis Abay II	169	169	169	169	169	169	169
Gilgel Gibe I	822	822	822	822	822	822	822
Diesel Plants	0	0	0	0	0	1	1
Tekeze	1,043	1,043	1,043	1,043	1,043	1,043	1,043
Gilgel Gibe II	1,912	1,912	1,912	1,912	1,912	1,912	1,912
Tana Beles	1,364	1,364	1,364	1,364	1,364	1,364	1,364
Adama 1 Wind	0	0	0	161	161	161	161
Ashegoda Wind Park	0	0	0	0	0	0	197
Messobo/Harena Wind Park	0	0	0	0	0	0	103
Ayisha wind Park	0	0	0	0	0	0	592
Amertinesh	0	0	0	0	0	0	215
GilgelGibeIII	0	5,300	5,300	5,300	5,300	5,300	5,300
Debre Birhan wind Park	0	0	0	0	0	0	197
Asela wind Park	0	0	0	0	0	0	197
Adama II wind Park	0	0	0	0	0	0	161

Genale Dawa III	0	0	0	1,600	1,600	1,600	1,600
Genale Dawa VI	0	0	0	0	1,475	1,475	1,475
Chemoga Yeda I	0	0	0	0	0	780	780
Chemoga Yeda II	0	0	0	0	0	134	568
Geba I	0	0	0	0	0	935	935
Geba II	0	0	0	0	852	852	852
Halele Warabesa-1	0	0	0	0	0	0	460
Halele Warabessa-2	0	0	0	0	1,570	1,570	1,570
Millennium Dam	0	0	0	0	5,240	15,177	15,177
Aluto Langano II	0	0	0	0	0	0	522
Tekeze II	0	0	0	0	0	1,730	1,730
Beko Abo	0	3,400	8,600	8,600	8,600	8,600	8,600
Border	0	0	5,769	6,000	6,000	6,000	6,000
Gibe 5TH	0	0	0	0	0	0	1,957
Wabi Shebele	0	0	0	0	0	460	460
Birbir	0	0	0	1,863	2,726	2,726	2,726
Lower Dedessa	0	0	0	3,208	3,208	3,208	3,208
Dabus	0	0	0	0	2,036	2,036	2,036
Tams	5,421	5,892	5,892	5,892	5,892	5,892	5,892
Genale Dawa 5th	0	0	0	655	655	655	655
Gibe IV	0	0	0	5,930	5,930	5,930	5,930
Gojeb	0	0	0	0	0	0	364
Mendaya	11,194	11,194	11,194	11,194	11,194	11,194	11,194
Tendaho	0	0	0	0	0	0	701
Corbetti	0	0	0	0	0	0	526
Abaya	0	0	0	0	0	0	701
Tulu Moya l	0	0	0	0	0	0	280
Dofan	0	0	0	0	0	0	420
Yayu	0	0	0	0	596	596	596
imported oil	0	0	0	0	0	141,234	141,234
imported coal	0	0	0	0	0	0	0
Total annual generation(GWh)	23,525	32,696	43,665	57,313	69,945	83,922	91,950
Total annual cost($millions)	3,710.01	2,994.58	3,924.97	5,633.53	6,596.34	8,073.38	7,943.19
Levelized cost($/MWh)	158	92	90	98	94	96	86
Annual investment cost ($millions)	2,723.80	1,013,471.80	2,074.20	3,156.55	3,618.23	4,495.14	3,817.19
Annual share of investment cost (%)	73%	54%	53%	56%	55%	56%	48%
Generation (GWh) from New Plants	16,615	9,171	10,969	13,648	12,632	14,047	7,958
Installed capacity (MW) from New Plants- @pf=53%[32]	3,579	1,975	2,363	2,940	2,721	3,026	1,714
Investment unit cost($/kW)	761	817	878	1,074	1,330	1,486	2,227

[32] *The average capacity factor of Ethiopian power system for all existing committed and candidate power plants is 53%*

Table A10: The result of model-2 in MATLAB LP solver with annual generation (GWh) of each generating power plants, and the total annual cost in the years 2011/12 to 2017/18.

Name of plant	Annual generation of each generating unit(GWh)						
	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
	Matlab	Matlab	Matlab	Matlab	Matlab	Matlab	Matlab
Koka	61	61	61	61	61	61	61
Tis Abay I	35	35	35	35	35	35	35
Awash II	140	140	140	140	140	140	140
Awash III	140	140	140	140	140	140	140
Fincha	704	704	704	704	704	704	704
Melkawakana	503	503	503	503	503	503	503
Altu Langano	17	17	17	17	17	17	17
Tis Abay II	169	169	169	169	169	169	169
Gilgel Gibe I	822	822	822	822	822	822	822
Diesel Plants	0	0	0	0	0	0	0.533
Tekeze	1,043	1,043	1,043	1,043	1,043	1,043	1,043
Gilgel Gibe II	1,912	1,912	1,912	1,912	1,912	1,912	1,912
Tana Beles	1,364	1,364	1,364	1,364	1,364	1,364	1,364
Adama 1 Wind	0	0	0	0	161	161	161
Ashegoda Wind Park	0	0	0	0	0	0	197
Messobo/Harena Wind Park	0	0	0	0	0	0	103
Ayisha wind Park	0	0	0	0	0	0	592
Amertinesh	0	0	0	0	0	0	215
GilgelGibeIII	0	2,262	5,300	5,300	5,300	5,300	5,300
Debre Birhan wind Park	0	0	0	0	0	0	197.37
Asela wind Park	0	0	0	0	0	0	197.37
Adama II wind Park	0	0	0	0	0	0	161
Genale Dawa III	0	0	0	1,084	1,600	1,600	1,600
Genale Dawa VI	0	0	0	0	0	1,475	1,475
Chemoga Yeda I	0	0	0	0	0	0	780
Chemoga Yeda II	0	0	0	0	0	0	568
Geba I	0	0	0	0	0	0	935
Geba II	0	0	0	0	0	852	852
Halele Warabesa-1	0	0	0	0	0	0	460
Halele Warabessa-2	0	0	0	0	0	1,570	1,570
Millennium Dam	0	0	0	0	0	11,106	15,177
Aluto Langano II	0	0	0	0	0	0	522
Tekeze II	0	0	0	0	0	0	1,730
Beko Abo	0	0	5,177	8,600	8,600	8,600	8,600
Border	0	0	0	6,000	6,000	6,000	6,000
Gibe 5TH	0	0	0	0	0	0	1,957
Wabi Shebele	0	0	0	0	0	0	460
Birbir	0	0	0	0	2,636	2,726	2,726
Lower Dedessa	0	0	0	0	3,208	3,208	3,208
Dabus	0	0	0	0	0	2,036	2,036
Tams	1,969	5,892	5,892	5,892	5,892	5,892	5,892
Genale Dawa 5th	0	0	0	0	655	655	655
Gibe IV	0	0	0	0	5,930	5,930	5,930
Gojeb	0	0	0	0	0	0	364
Mendaya	11,194	11,194	11,194	11,194	11,194	11,194	11,194
Tendaho	0	0	0	0	0	0	701
Corbetti	0	0	0	0	0	0	526
Abaya	0	0	0	0	0	0	701
Tulu Moya l	0	0	0	0	0	0	280
Dofan	0	0	0	0	0	0	420
Yayu	0	0	0	0	0	596	596
Imported oil	0	0	0	0	0	0	141,234
Imported coal	0	0	0	0	0	0	0
Total annual generation(GWh)	20,073	26,258	34,473	44,980	58,086	75,811	90,817
Total annual cost($millions)	3,122	2,385	3,216	4,370	6,108	9,259	10,661

Levelized cost($/MWh)	156	91	93	97	105	122	177
Annual investment cost ($millions)	2,137	1,065	1,451	2,037	3,065	5,257	6,489
Annual share of investment cost (%)	68%	45%	45%	47%	50%	57%	61%
Generation (GWh) from New Plants	13,163	6,185	8,215	10,507	13,106	17,725	16,139
Installed capacity (MW) from New Plants-@pf=53%	2,835	1,332	1,769	2,263	2,823	3,818	3,476

Appendix B

MATLAB codes:

Code 1

```
% Programmer: Girmaw Teshager
% Date:  16-May-2011
% Program: This program plots the electricity demand forecast in
% Ethiopia within the years of 2003/04 and 2019/20
function generation(X1, YMatrix1)
%CREATEFIGURE2(X1,YMATRIX1,X2,YMATRIX2)
%  X1:  vector of x data
%  YMATRIX1:  matrix of y data
%  X2:  vector of x data
%  YMATRIX2:  matrix of y data
% Create figure
figure1 = figure;
% Create axes
axes1 = axes('Parent',figure1);
box(axes1,'on');
grid(axes1,'on');
hold(axes1,'all');
%load data
model1=[23525   32696   43665   57313   69945   83922];
model2=[20073   26258   34473   44980   58086   75811];
differ=model2-model1;
YMatrix1=[model1;model2;differ];
%limit time series
X1=2004:2009;
% Create multiple lines using matrix input to plot
plot1 = plot(X1,YMatrix1,'Parent',axes1,'LineWidth',3);
set(plot1(1),'Color',[1 0 1],'DisplayName','Model-1');
set(plot1(2),'Color',[0 1 1],'DisplayName','Model-2');
set(plot1(3),'Color',[0 1 0],'DisplayName','Difference');
% Create xlabel
xlabel({'Year (E.C.)'});
% Create ylabel
ylabel({'Generation (GWh)'});
% Create light
light('Parent',axes1,...
         'Position',[-0.0001 1 0.0001]);
% Create legend
legend1 = legend(axes1,'show');
set(legend1,...
```

Code 2

```
% Programmer: Girmaw Teshager
% Date:  18-May-2011
% Program: This program plots the Ethiopian GDP by main sectors
% and their total
```

```
function gdp(X1, YMatrix1)
%CREATEFIGURE1(X1,YMATRIX1)
% X1:  vector of x data
% YMATRIX1:  matrix of y data
% create figure
figure1 = figure;
% create axes
axes1 = axes('Parent',figure1);
box(axes1,'on');
hold(axes1,'all');
%load data
Agriculture=[-10.5  16.9    13.5    10.9    9.4 7.5 6.4];
Industry=[6.5   0.7 9.4 10.2    10.2    10.4    9.9];
Services=[6 6.2 12.8    13.3    14.3    17  14];
Total=[-2.1 11.7    12.6    11.5    11.5    11.6    10.1];
Ymatrix=[Agriculture;Industry;Services;Total];
%limit time series
Year=1995:1:2001;
% Create multiple lines using matrix input to plot
plot1 = plot(Year,Ymatrix,'Parent',axes1,'LineWidth',2);grid on
set(plot1(1),'DisplayName','Agri','color',[0 1 0]);
set(plot1(2),'DisplayName','Industry','color',[1 0 1]);
set(plot1(3),'DisplayName','Services');
set(plot1(4),'DisplayName','Total','linewidth',3,'color',[0 0 1]);
% Create xlabel
xlabel({'Year (E.C.)'});
% Create ylabel
ylabel({'Growth rate (%)'});
% Create title
title({'Ethiopian GDP Growth Rate'});
% Create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.66 0.39 0.19 0.19]);
```

Code 3

```
% Programmer: Girmaw Teshager
% Date:  19-May-2011
% Program: This program displays the result on the MATALB command lines
% and plots the generation of power plants for annual demand
%load the coefficients of single-objective function of LP for model-1
f01=input('Enter coefficients of objective function for model-1\n');
% load the coefficients of single-objective function of LP for model-2
f02=input('Enter coefficients of objective function for model-2\n');
%enter the row of elements of non-linear constraints matrix
aa=input('Enter the elements of nonlincon\n');
bb=input('Enter the elements of nonlincon\n');
A=[aa;bb];
%enter the RHS of matrix elements of linear inequality constraints matrix
b=input('Enter the RHS of nonlincon\n');
f01=f01';
f02=f02';
%enter the elements of linear equality constraint matrix
```

```
Aeq=input('Enter the elements of equality constraint\n');
%limit the non-negativity of the variable
lb=zeros(53,1);
%limit the upper bound of the variable
ub=input('Enter the vector of maximum capacity of units\n');
ub=ub';
%limit start-up of iteration
x0=lb;
%enter the matrix of fuel
k=input('Enter the number of fuel types\n');
fk=zeros(k,1);
%load the investment unit cost
inv=input('Enter the Investment unit cost\n');
inv1=inv';
inv1=[inv1;fk];
inv2=inv1;
%select the solver and display the iteration
options=optimset('largescale','off','simplex','on','display','iter');
%enter the time horizon in which the the planning is implemented
    y=input('Enter number of planning years\n');
while y>1
  beq1=input('Enter yearly demand for model-1\n');
  beq2=input('Enter yearly demand for model-2\n');
  f1=f01+inv1;
  f2=f02+inv2;
  %create plot
  [x1fopt1exitflag1output1 lambda1]=linprog(f1,A,b,Aeq,beq1,lb,ub,x0,options)
  [x2fopt2exitflag2 output2 lambda2]=linprog(f2,A,b,Aeq,beq2,lb,ub,x0,options)
   % set unit matrix with the size of objective function matrix
  I=ones(size(f1));
  %set updated investment unit cost on the basis of utilizing of power plants
  inv1=inv1.*(I-ub.\x1);
  inv2=inv2.*(I-ub.\x2);
  %set the decrement of planning years
  y=y-1;
  %limit x-coordinate for design parameters
  xx=1:1:53;
  %create the plot
  [AA H1 H2]=plotyy(xx,x1,xx,x2,'plot');grid on;
  %create ylabels
  set(get(AA(1),'ylabel'),'string','Generation (MWh):Model-1')
  set(get(AA(2),'ylabel'),'string','Generation (MWh):Model-2')
  %create line properties
  set(H1,'linewidth',2,'linestyle','h');
  set(H2,'linewidth',3)
  %create xlabel
  xlabel('ith number of decision variables')
  %Create legend
  legend1 = legend('show');
  set(legend1,...
    'Position',[0.74 0.84 0.10 0.064]);

end
```

Code 4

```
% Programmer: Girmaw Teshager
% Date:  22-May-2011
% Program: This program plots the annual generation growth for model-1
% and model-2 in the years of 2011/12 to 2016/17
function generation(X1, YMatrix1)
%CREATEFIGURE2(X1,YMATRIX1,X2,YMATRIX2)
% X1:  vector of x data
% YMATRIX1:  matrix of y data
% X2:  vector of x data
% YMATRIX2:  matrix of y data
% create figure
figure1 = figure;
% create axes
axes1 = axes('Parent',figure1);
box(axes1,'on');
grid(axes1,'on');
hold(axes1,'all');
%load data
model1=[23525   32696   43665   57313   69945   83922];
model2=[20073   26258   34473   44980   58086   75811];
differ=model2-model1;
YMatrix1=[model1;model2;differ];
%limit time series
X1=2004:2009;
% Create multiple lines using matrix input to plot
plot1 = plot(X1,YMatrix1,'Parent',axes1,'LineWidth',3);
set(plot1(1),'Color',[1 0 1],'DisplayName','Model-1');
set(plot1(2),'Color',[0 1 1],'DisplayName','Model-2');
set(plot1(3),'Color',[0 1 0],'DisplayName','Difference');
% create xlabel
xlabel({'Year (E.C.)'});
% create ylabel
ylabel({'Generation (GWh)'});
% Create light
light('Parent',axes1,...
    'Position',[-0.0001 1.0 0.0001]);
% create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.5 0.6 0.2 0.3]);
```

Code 5

```
% Programmer: Girmaw Teshager
% Date:  23-May-2011
% Program: This program plots the total annual cost for model-1 and
% model-2 in the years of 2011/12 to 2016/17
function cost(X1, YMatrix1)
%CREATEFIGURE2(X1,YMATRIX1,X2,YMATRIX2)
% X1:  vector of x data
% YMATRIX1:  matrix of y data
% X2:  vector of x data
% YMATRIX2:  matrix of y data
% create figure
```

```
figure1 = figure;
% create axes
axes1 = axes('Parent',figure1);
box(axes1,'on');
grid(axes1,'on');
hold(axes1,'all');
%load data
model2=[3122    2385    3216    4370    6108    9259];
model1=[3710    2995    3925    5634    6596    8073];
YMatrix1=[model1;model2];
%limit time series
X1=2004:1:2009;
% Create multiple lines using matrix input to plot
plot1 = plot(X1,YMatrix1,'Parent',axes1,'LineWidth',3);
set(plot1(1),'Color',[0 1 0],'DisplayName','Model-1');
set(plot1(2),'Color',[1 0 0],'DisplayName','Model-2');
% Create xlabel
xlabel({'Year (E.C.)'});
 % Create ylabel
ylabel({'Total annual cost ($millions)'});
 % Create light
light('Parent',axes1,...
    'Position',[-0.0001 1.0 0.0001]);
 % create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.5 0.6 0.2 0.3]);
```

DECLARATION

I, the undersigned, declare that this thesis work is my original work, has not been presented for a degree in this or any other universities, and all sources of materials used for the thesis work have been fully acknowledged.

Name: Girmaw Teshager Signature: ________________

Place: Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa

Date of submission: June 8, 2011

This thesis has been submitted for examination with my approval as a university advisor.

Prof. Wolde-Ghiorgis, Woldemariam Signature: ________________

Advisor's Name