

Policy Options for the Sustainable Development of the Power Sector in Zambia

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**Energy Research Centre
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Declaration

I, Bernard Tembo, declare that this thesis is my original work, except where stated otherwise. This thesis is being submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering (Sustainable Energy Engineering) at the University of Cape Town. It has not been submitted before for any degree or examination in any other University.

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Dedication

To my late mother and father (Eunice Nyirenda Tembo & Shemu Tembo) and their grand children.

B. Tembo

University of Cape Town

Acknowledgments

I am grateful to my Lord Jesus Christ for preserving my life, and also for enabling me to complete my studies at University of Cape Town in good health.

My heart is full of gratitude for the supervisory guidance I received from Ms Alison Hughes and Mr Bruno Merven. My supervisors' questions, insights and words of encouragement meant a great deal to me. I also had a unique privilege to find a friend in Mr Merven.

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Abbreviations and Acronyms

UNFCCC	United Nations Framework Convention on Climate Change
IPCC	Intergovernmental Panel on Climate Change
ENSO	El Nino-Southern Oscillation
SADC	Southern Africa Development Community
SAPP	Southern Africa Power Pool
LEAP	Long-range Energy Alternative Planning system
MESSAGE	Model for Energy Supply Strategy Alternative and their General Environmental Impacts
MEAD	Model for Energy Analysis Demand
RE	Renewable Energy
RSA	Republic of South Africa
MEWD	Ministry of Energy and Water Development
MFNP	Ministry of Finance and National Planning
TAZAMA	Tanzania-Zambia Mafuta
JICA	Japan International Cooperation Agency
WCD	World Commission on Dam
GRZ	Government of the Republic of Zambia
ZESCO	Zambia Electricity Supply Co-operation
TIMES	The Integrated Markal EFOM system
IEA	International Energy Agency
IAEA	International Atomic Energy Agency
IMF	International Monetary Fund
ERB	Energy Regulation Board

Abstract

Many climate change studies project that occurrence of droughts (due to dry years) in Southern Africa will increase; this raises concerns over Zambia's electricity system. Currently, over 99% of Zambia's electricity is supplied by hydropower, which is vulnerable to droughts. With Zambia targeting to be a middle income industrialised country by 2030, it is important that the impacts of droughts on the electricity system are understood, and how the system's adaptive capacity can be improved. This is imperative if the system were to enhance economic development. The main focus of this research therefore, was to develop an understanding of how Zambia's electricity system would evolve in different economic and climatic scenarios. A comprehensive electricity model for Zambia was developed after reviewing literature on Zambia's electricity sector and energy planning in a developing country context. A Scenario planning approach was used to model and analyse the electricity system that would be required to meet demand in two climatic scenarios (average and dry year river-flows) and for different economic growth scenarios. The results showed that the supply system has to be increased in order to support economic development. In a dry year scenario, the availability of the hydro technologies reduces significantly and this leads to a considerable increase in the average generation cost of the system. The introduction of renewable energy and coal technologies into the system lessens the impacts of droughts. Carbon emitting technologies such as coal and oil are still viable supply options even with a carbon price of \$50 per tonne. Only low and base-case growth scenarios need an explicit diversification policy since least cost policy in the high growth scenario (the middle income growth trajectory) leads to a diverse supply system. Implementing a diversification policy in the high growth scenario increases average generating cost without improving the system's adaptive capacity. The most cost effective way of increasing the system's adaptive capacity is by importing electricity and gradually increasing share of renewable and coal technologies in the system. Further research on how electricity trade in Southern Africa could be enhanced, should be done.

Keywords: *Zambia, energy planning, hydro technology, climate change, climate variability, electricity trade*

1. Introduction

1.1. Background

Zambia is one of the 15 Southern African Development Community (SADC) countries; with a land area of 752 614 square kilometres. The Savannah woodlands cover much of the land. The main rivers are the Zambezi, Kafue, Luangwa and Luapula. The country has generally four distinct seasons: cool and dry (April to August); hot and dry (September to October); hot and wet (November to January) and cool and wet (February to May) (Zesco 2008).

The population in 2010 was about 13.1 million people (CSO 2011), with about 40% living in urban areas and the rest living in rural areas. In 2008, per capita annual income purchasing power parity (ppp) was \$1278 (2005 constant international dollar price), with a GDP of \$15.82 billion (World Bank 2011). Until recently, per capita income had been declining due to low economic activities, mainly in the mining & quarry sub-sector which is the backbone of the Zambia's economy.

Despite these historical fluctuations in economic activities, Zambia hopes to take a strong and dynamic path to become an industrialised middle income country by 2030 (GRZ 2006). The economy is projected to grow at rate of 9%, with the mining & quarry sub-sector growing at 7.6%. Among many other embodying values, Zambia aspires to promote sustainable development.

1.2. Research Problem

There still remain significant challenges to achieving the industrialised middle income target, such as limited electricity infrastructure to support economic development and low levels of access to safe and clean energy for the majority of the population.

National electrification rate in 2008 was about 21%, with only 3.2% of the total households (HH) in rural areas having access to electricity (ERB 2008; GRZ 2011). The households that are not electrified rely on traditional fuels (wood fuel, crop residues and charcoal), kerosene and candles for their cooking, heating and lighting. The majority of the population is excluded from the benefits of national development. Zambia, however, plans to increase access to safe and clean energy by developing a reliable and sustainable energy supply system (MEWD 2008).

In order to increase the electricity supply capacity, Zambia has commissioned the construction of four hydro plants: Itezhi Tezhi, Kafue Gorge Lower, Kariba North Bank Extension and Kabompo plants. Other power projects earmarked for development are Maamba Coal, Batoka Gorge, Devil's Gorge, Kalungwishi and some other smaller hydro plants (GRZ 2011).

Considering that currently over 99% of electricity comes from hydropower and that all the projects being developed are hydro plants, makes Zambia's electricity system vulnerable to droughts. Droughts lead to reduction in run-off water which is needed for electricity generation. The impacts of a dry year could be devastating, as was the case during the 1991/2 drought, where Zambia incurred a loss of about US\$300 million (Kandji et al. 2006). Similar impacts were recently observed in East African countries (GNESD 2009). In addition, occurrences and frequencies of dry year in southern Africa are expected to increase which would further compromise hydropower dominated systems (Harrison 2001; Harrison & Whittington 2002; Tadross et al. 2005; Yamba et al. 2011).

If Zambia's electricity system is to enhance economic development, it is imperative that the system be diversified. Diversifying the system from hydropower would make it more resilient to climatic events such as droughts¹. This would improve energy security.

1.3. Thesis Question and Objectives

Threats to Zambia's electricity system have been highlighted in the preceding sections. There was a need to better understand the extent to which a dry year can affect the electricity system, specifically the impact on the cost of generating electricity. Given the risks of having a hydro-dominated supply system, there was a need to assess other supply options such as other renewable energy, oil, gas, and coal technologies.

In summary, this research sought to answer the following question:

What electricity generation expansion plan should Zambia develop in order to achieve the 2030 development target?

The overall objective of this study was to give decision and policy makers a clearer picture of the main issues in Zambia's electricity sector.

¹ Climate resilience is the ability of a system to "absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change" (Ebinger & Vergara 2011: 104).

In order to fulfil the overall objective, the following were the specific objectives of the study:

1. To develop a baseline of electricity consumption in Zambia.
2. To develop a demand model for projecting electricity demand in Zambia.
3. To model Zambia's electricity supply system.
4. To explore technology options that can be developed to meet growing electricity demand.
5. To propose strategies and a plan (based on the results of the analyses) that would enhance sustainable development.

1.4. Methodological Approach

This research collated data from published sources. The data was then integrated into energy models for projections and analysis. The demand model was developed using Long-term Energy Alternative Planning system (LEAP) while the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) was used for the supply model. Scenario planning approach was used because of its adequacy to capture and represent uncertainty (Soontornrangson et al. 2003; Rachmatullah et al. 2007). In the demand model, three economic scenarios were developed. For the supply model two climatic scenarios, average and dry year, were considered.

1.5. Thesis Outline

This thesis consists of five chapters with appendices.

Chapter 1 gives Zambia's background and highlight the threats to the electricity system. This chapter also gives the motivation and relevance of the research.

Chapter 2 reviews issues surrounding energy and electricity expansion planning in Zambia. It also explains possible risks that Zambia electricity system could face due to climatic changes. Options to reduce these system risks are also discussed.

Chapter 3 describes the data collection process, gives the assumptions and explains the methodology that was used when building the models. The chapter also highlight the limitations of the tools and methods used.

Chapter 4 examines and discusses the results of the models as described in Chapter 3 and also proposes a future electricity plan for Zambia.

Chapter 5 presents the conclusions and recommendations of the research.

2. A review of Zambia's energy system and expansion options

2.1. Introduction

This chapter examines the main issues in long-term energy planning, particularly electricity expansion planning, in Zambia. It also looks at how energy, environmental and economic systems interact and how they reinforce each other. Within this chapter, Zambia's electricity consumption baseline and electricity supply reference system are established, and technology options that could be used to supply electricity are explored. Critical issues that should be considered in developing an environment friendly and climate resilient system are also highlighted. The chapter concludes with a summary of key emerging issues.

2.2. Energy Utilisation in Zambia

Zambia is well endowed with many different energy resources, such as wood fuel, charcoal, coal, imported oil, hydropower, and other renewable resources. However, energy consumption is mainly dominated by wood fuel and charcoal (traditional fuels). In 2008, Zambia's total energy consumption was 245.25 PJ, of which traditional fuels accounted for 81% of consumption (MEWD 2008; IEA 2011) as shown in figure 2.1 below.

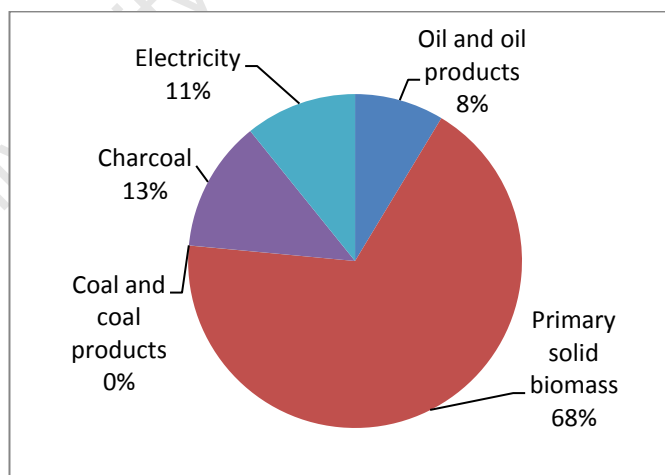


Fig 2.1 Final Energy Consumption by fuel in Zambia in 2008 (IEA 2011)

Zambia's energy consumption is usually divided into six sectors namely industrial, commercial, social services, transport, agriculture and forestry, and residential. However, for the purpose of this study, these categories have been re-categorised into four sectors namely services, industrial, agricultural and residential (a detailed description of the sectors is given

in Section 3.5.2). In 2008, the share of total final energy and electricity consumption by these sectors are as shown below in figures 2.2 and 2.3 respectively.

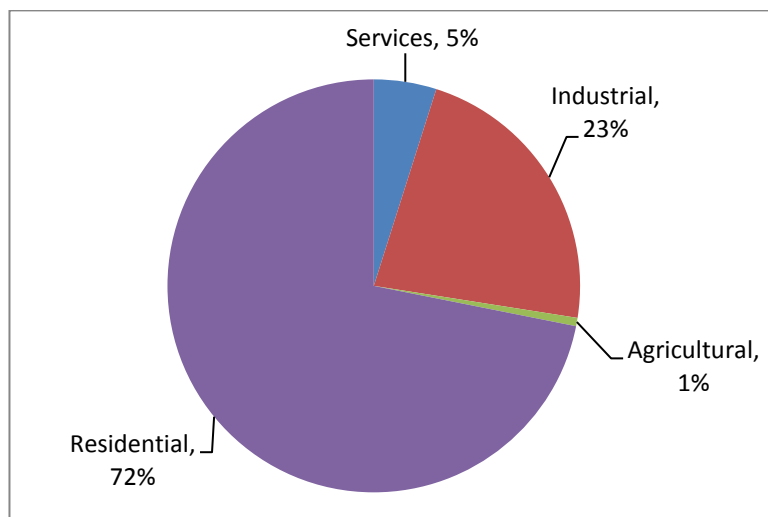


Fig 2.2 Consumption of final energy by sectors in Zambia (IEA 2011)

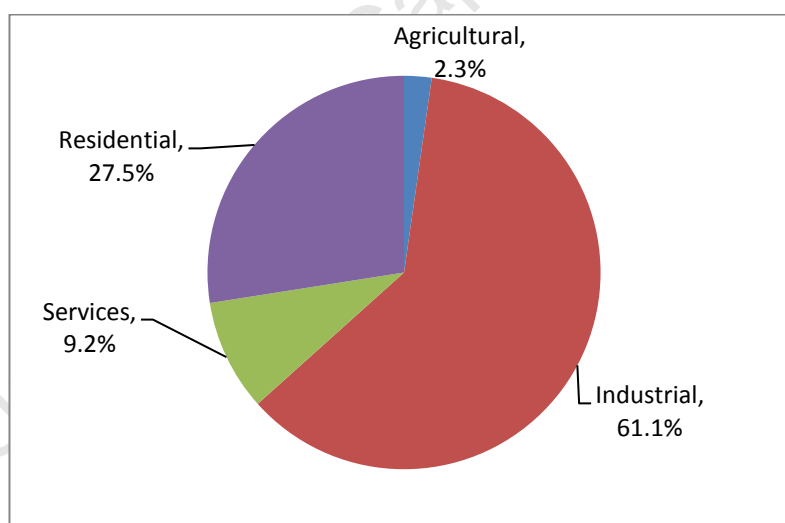


Fig 2.3 Consumption of final electricity by sectors in Zambia (IEA 2011)

2.3. Primary Energy Supply

Energy supply is made up of primary energy resources and energy transformation. Primary energy is an energy form that is in a raw state while energy transformation is the process by which primary energy is converted into a usable energy form (Blok 2007). However, some primary energy resources such as coal, solar and wood fuel can be used in their raw state.

Zambia has a wide range of primary energy resources, of which all of them are locally available except for oil. These local resources include biomass, coal, uranium, hydro, solar, wind and geothermal (MEWD 2008).

2.3.1. Biomass

Zambia has vast biomass resources (Chidumayo et al. 2002). Biomass resources include all organic matter such as wood fuel, charcoal, dung, plant waste, municipal waste and energy crops (MEWD 2008). This energy form supplies the majority of Zambia's energy requirements albeit in a non-commercial way.

In 2008, the use of biomass accounted for 96% of the total energy use in the residential sector, and this sector consumed 85% of the total consumed biomass (IEA 2011). Thus, biomass plays an important role in Zambia's residential sector, where most of the people are not connected to electricity. Biomass is also a vital form of energy in the agricultural sector (where small-scale farming is a major activity), where it is used for processing agricultural produce. On the other hand, commercial use of biomass in Zambia has not yet been developed. For instance, despite having a developed sugar industry, most of the bi-products of sugar cane are not processed into gel gas or other forms of bio-fuels or even for production of electricity.

2.3.2. Coal

The coal reserves are estimated to be over 30 million tonnes with probable resources in other parts of the country (MEWD 2008). However, the usage of coal is very minimal. This low usage could mainly be attributed to unreliable mining output from the Maamba Collieries (the current operators of coal mines) which in turn has forced coal end-users (mainly the industrial sector) to find an alternative.

Currently, Maamba Collieries has processing capacity of one million tonnes per year. The mines produce bituminous coal with a heating value of about 27.12 GJ/tonne (MEWD 2008). Therefore, with the right investment in the coal industry, coal could offer a pathway for diversification in the energy system especially the electricity sub-sector which is heavily reliant on hydropower.

2.3.3. Uranium

Even though Zambia's Lumwana Mines produces uranium, energy supply from nuclear technology is not yet developed. Further, due to long-term technical and human resource

requirements, it would take a while for nuclear energy to start contributing to Zambia's energy sector.

2.3.4. Hydropower

The electricity sub-sector is dominated by hydropower, which supplies about 99.9% of the electricity (IEA 2011). Hydropower is also the second most used energy source after biomass in Zambia.

Zambia has potential of about 6 000 MW (MEWD 2008) and an installed capacity of 1 889 MW. Development of this potential could also play a major role in off-setting the greenhouse gas (GHG) emissions in the SADC region. This could also put Zambia in a good position of exporting environment friendly electricity.

2.3.5. Renewable Sources

Despite enormous potential of renewable energy (RE) resources such as solar, geothermal, energy crop, plant and animal waste, wind and mini-hydro, commercial utilisation of these resources is still low. However, there have been considerable efforts to increase participation of renewables in the energy sector (MEWD 2008; GRZ 2011).

With a solar energy radiation of about 5.5 kWh/m²/day (MEWD 2008) in Zambia, solar could play a significant role in the supply of electricity. Thus, with the right investments, policies and institutional framework, RE could conveniently be used to supply electricity.

In addition, using RE to supply electricity would enhance the electrification process. This could in turn encourage sustainable development, as it could stimulate and promote local economic activities (Vera & Langlois 2007; Haanyika 2008). However, the economics of RE currently prohibit the maximum utilisation of RE technologies in Zambia, but with technology learning the future of RE looks optimistic.

2.3.6. Oil

There are no proven oil resources in Zambia, and all oil requirements are imported. The main import route is through the TAZAMA pipeline which runs from Tanzania to Ndola for a distance of about 1 706 kilometres (MEWD 2008), with some of the imports coming in through road and rail.

Currently, Zambia only has one oil refinery which is based in Ndola; with a processing capacity of about 1.1 million tonnes per annum (MEWD 2008). However, some of the refined oil products are imported directly to meet demand. There have been talks to expand the oil

refining capacity in the country; which could also facilitate the importation of oil from neighbouring Angola. Some oil exploration works are also under way in different parts of Zambia.

2.4. Electricity System

Currently, the supply of electricity is mainly from hydropower. The total installed generation capacity² is 1 899 MW of which 99.5% are hydropower plants and the balance is from oil plants. The installed capacities of plants are Kafue Gorge (990 MW); Kariba North Bank (720 MW); Victoria Falls (108 MW); Lunsemfwa and Mulungushi (47 MW); mini-hydro plants (24 MW); and isolated oil generators (10 MW). There are also standby gas turbines of 80 MW owned by Copperbelt Energy Corporation (CEC) which have not been used in a long time (ERB 2008; JICA/MEWD 2009).

The hydro plants are mainly located in the Zambezi river basin; all of them except Lunsemfwa, Mulungushi and all mini hydro plants are based in the southern part of the country. The Utility company (ZESCO) owns 1 852 MW, while the other 47 MW and the 80 MW standby are owned by Lunsemfwa Hydro Power Company (LHPC) and CEC respectively.

There are currently four Independent Power Producers (IPPs) in the electricity sub-sector (ERB 2008): CEC, LHPC, Zengamina Hydro Power Company (ZHPC) and North-western Energy Company (NEC).

2.4.1. Kafue Gorge Power Station

Kafue Gorge (KG) Power station is currently the largest single plant in Zambia. It was initially designed with a capacity of 900 MW (with six 150 MW units) but was later upgraded to 990 MW (ERB 2008). The station is on the Kafue River and is operated as a run-of-river station, with an average plant factor (CF) of 77%.

Water inflow to the station is regulated by the Itezhi Tezhi dam upstream. From the dam, the river flows through the Kafue flats (covers an area of about 5 000 sq Km), where a significant amount of water is lost due to evaporation. However, flow into the station is generally stable and predictable due to the regulating dam.

Figure 2.4 below shows the generalised relationship between observed total monthly water inflow of the river and power output from the station in an average year.

² Appendix A. Table A1 the techno-economic data for existing stations

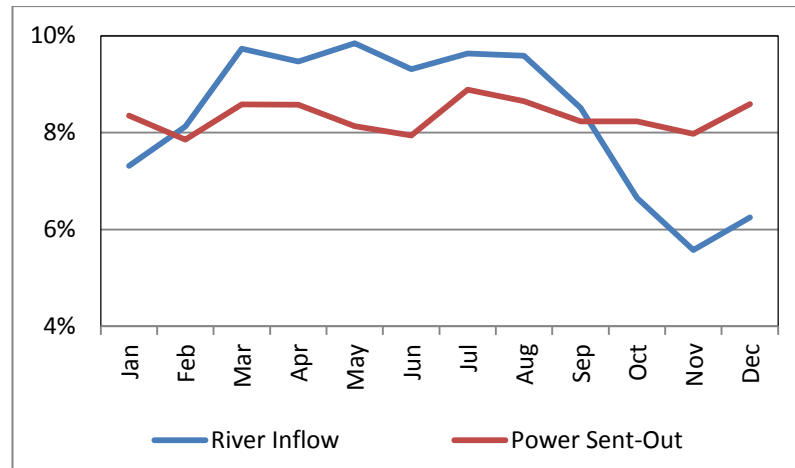


Fig 2.4 Share of the total river inflows and power output of the KG station (based on author's analysis)

2.4.2. Kariba North Bank Power Station

The Kariba Dam was a collaborative effort between the then Northern and Southern Rhodesian (now Zambian and Zimbabwean respectively) governments in the 1950s. This complex (located on the Zambezi River) was initially designed to host power stations that would produce a total of 1320 MW, between the north and south banks. The north bank (which is the Zambian part) was designed to have a capacity of 600 MW with the main purpose of meeting the increasing electricity demand from the Industrial sector. The plant was commissioned in 1976 and has since been in production (WCD 2000; IMF 2008).

The station is operated as reservoir plant, with an average plant factor (CF) of 65% (Nexant 2007). It was recently upgraded from 600 MW (with 150 MW units) to 720 MW (with 180 MW units) (ERB 2008). With an enormous water volume of 180.6 cubic kilometres the Kariba Dam, the KNB station is not usually affected by drought; except when the droughts are extreme and prolonged (Mukheibir 2007). Figure 2.5 below shows the generalised relationship between observed monthly water inflow into the dam and power output for the station in an average year.

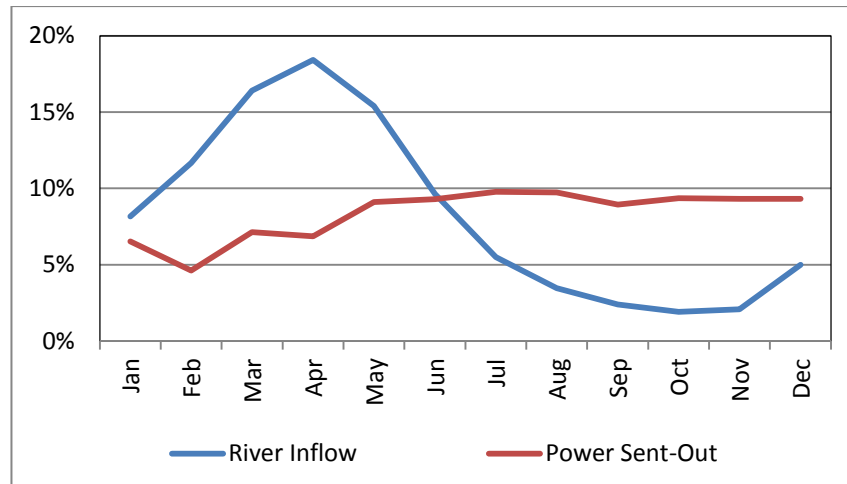


Fig 2.5 Share of the total river inflows into the dam and power output of the KNB station (based on author's analysis)

2.4.3. Victoria Falls Power Station

This is the second oldest (after Mulungushi plant) of all Zambia's hydro plants. The development of the station started in the 1930s and since then, a number of rehabilitations have been done to improve its output and increase its service life. The plant is on the Zambezi River, just below the Victoria Falls. It is operated as a run-of-river plant, with an average plant factor (CF) of 71% (Nexant 2007).

The current installed capacity (after the rehabilitation works in the 2000s) is 108 MW. Figure 2.6 below shows the generalised relationship between observed monthly river-flow (as measured at Victoria Falls (VF) station) and power output from the station in an average year. It should be noted however, that water inflow into the plants is controlled by a channel from the river. Thus, power output from the station is not closely linked to the river-flow, since the station can still operate at relative lower river-flow volume.

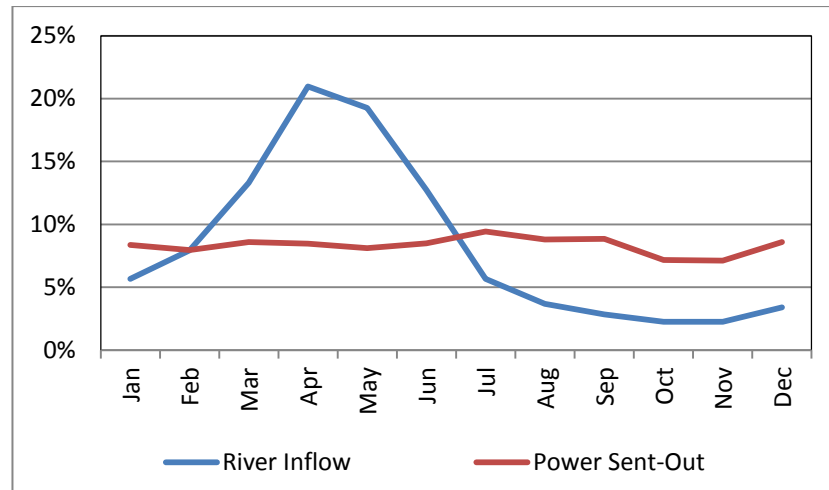


Fig 2.6 Share of the total river-flow and power output of the VF station (based on author's analysis)

2.4.4. Lunsemfwa Power Station

There are two power stations run by LHPC: Lunsemfwa (18 MW) and Mulungushi (28.5 MW) stations (JICA/MEWD 2009). These plants are hugely affected by droughts because they are operated as run-of-river and are also on a river that supplies irrigation water to one of the largest farming blocks in the country, Mkushi Farming block.

Figure 2.7 shows the effect that a drought season of 2005/2006 (only 50% of the normal rainfall was recorded) had on the power output of the plant (JICA/MEWD 2009).

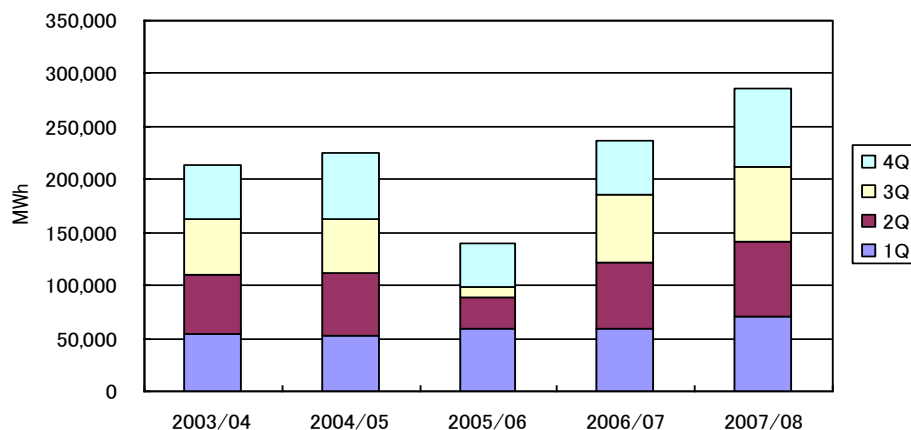


Fig 2.7 Power generation output from LHPC (JICA/MEWD 2009)

2.4.5. Mini hydropower Plants

ZESCO operates all the four mini-hydropower plants (Lunzua, Chishimba Falls, Musonda Falls and Lusiwasi). The combined installed capacity of these plants is 24 MW (JICA/MEWD 2009). These plants are operated as run-of-river. Based on the 2007/08 electricity output, their average plant capacity factor is 29%.

2.4.6. Isolated Oil Generators

These generators are located in different parts of the country. These plants were put in place for electrification purposes; grid electrification was too expensive to be an option. Thus, these plants were designed to be operated as base-load plants as long as fuel was available.

However, because the costs of operating these plants are high, continuous supply from these plants are neither financially nor economically viable. Thus, ZESCO has started phasing them out in favour of grid connection; as in the case of Chama generator set (ERB 2008).

2.4.7. Copperbelt Energy Corporation Plants

As mentioned earlier, CEC has an 80 MW gas turbine capacity for standby emergency supply to the mines (ERB 2008). However, these plants have not supplied electricity in a long time.

2.4.8. Transmission and Distribution Network

Transmission and distribution is done by ZESCO and CEC, with CEC mainly focused on the Copperbelt and North Western provinces mining firms. The majority of transmission and distribution is done by ZESCO (ERB 2008).

The transmission network operates voltages of 66kV and above, with an average loss of about 3.5%; while the distribution network has a voltage between 0.4kV and 66kV. The distribution network has an average loss of 20.74% (IPA 2007; ZESCO 2009).

2.4.9. Load Profile

Between 2000 and 2006, electricity demand in Zambia grew at an annual average rate of about 6%. This was largely influenced by the increase in demand from the industrial (especially the mining & quarry sub-sector) and residential sectors. Thus, because of the rehabilitation work in the 2000s and with growing demand, Zambia reduced its exports and increased its imports of electricity.

The yearly load curves in figure 2.8 below, shows that there is high demand of electricity from July to December. There are a number of reasons that could lead to this, some of them are:

1. Increase in heating and cooling requirements in both the residential and services sectors.
2. Increased processing and mining activities in the agricultural sector and mining & quarry sub-sector respectively.

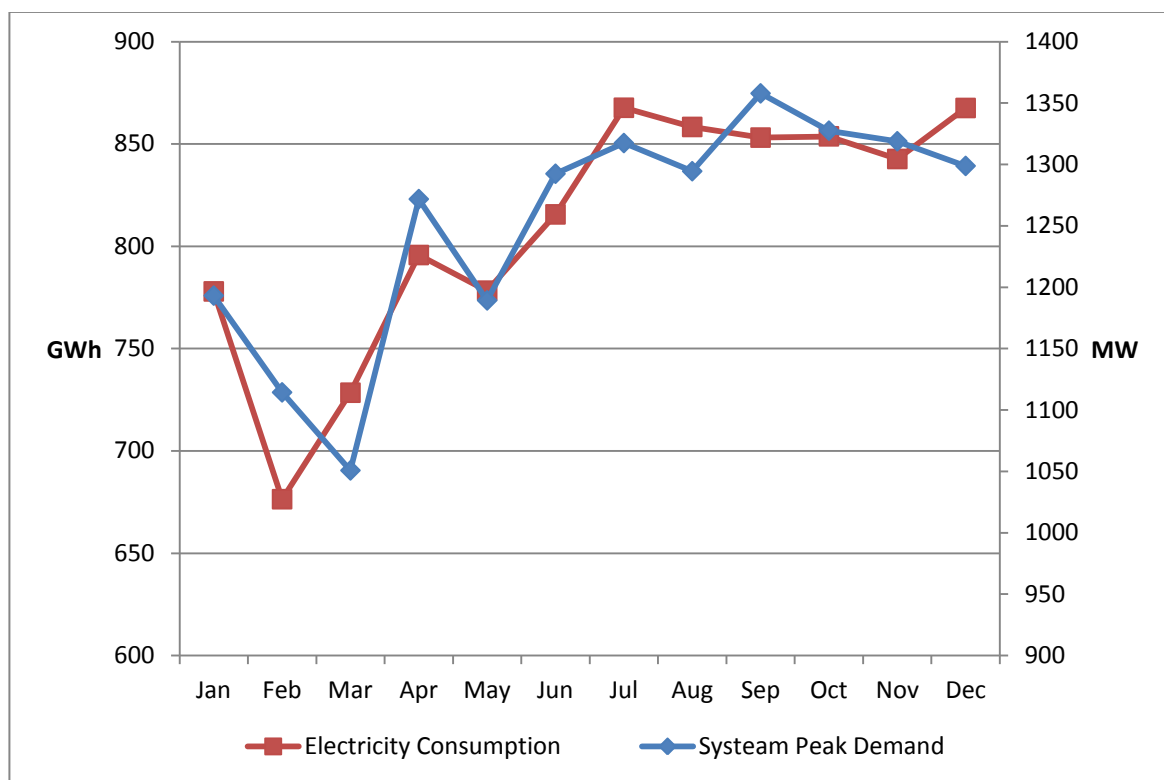


Fig 2.8 2008-Yearly Load curve of secondary electricity consumption and system peak demand (based on the author's analysis of historical demand)

The load profile (as shown in figure 2.9 below) can be divided into four parts, with notable peaks in the morning, lunch and evening times. However, the shape of the profile changes from day-to-day and month-to-month depending on, among others, economic activity, seasonality, and usage habits (Huang and Wu 2008). As noted earlier, due to the rehabilitation work, the installed generation capacity in 2008 was about 1 734 MW, and the supply of electricity was characterised by massive load shedding. Nonetheless, these load shedding events did not affect the mining & quarry sub-sector due to contractual supply agreements (IMF 2008; World Bank 2008); the residential sector was the most affected. Therefore, if demand continues to increase without building more supply capacity, the social and economic (with exception of the mining & quarry sub-sector) sectors would be hugely affected. This could undermine efforts to encourage sustainable development. Fig 2.9 below shows the averaged daily load profile.

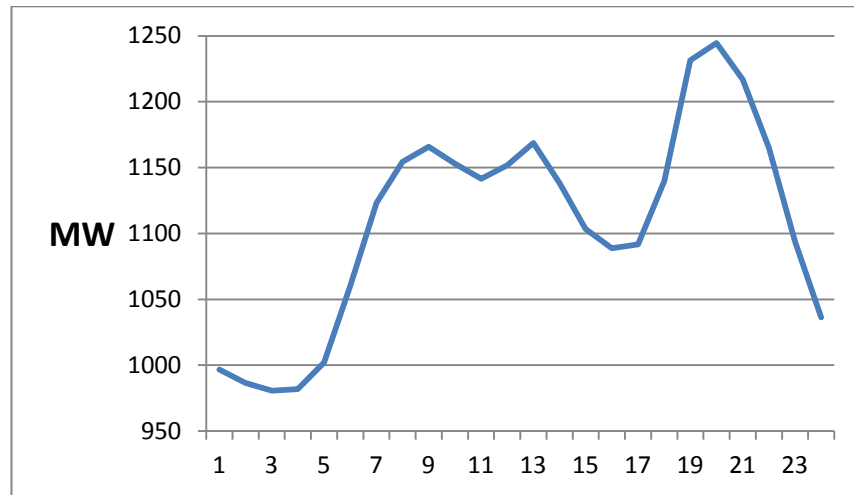


Fig 2.9 Average daily load profile for 2008 secondary electricity consumption (based on the author’s analysis)

2.5. Potential Power Station Sites

In order to continuously support development, Zambia has identified a number of potential plants sites³. Nevertheless, most of these potential projects have not yet secured finances for their development; except for Kariba North Bank Extension (360 MW), Kafue Gorge Lower (750 MW), Itezhi Tezhi (120 MW) and Kabompo (40 MW) projects. Other potential projects are Kalungwishi (240 MW), Maamba Coal (500 MW), Batoka Gorge (800 MW) and Devil’s Gorge (600 MW). There are also generic projects based on the potential of a particular technology such as solar, hydro and coal.

It should be noted, however, that all these potential projects are hydropower except for Maamba Coal project. Thus, with possible future climatic changes, it is a concern that little is known of how supply of electricity could be impacted.

2.6. Energy System Planning

Energy planning is a systematic and deliberate process of bringing together information of energy supply and demand with their related issues, so that a comprehensive energy system can be developed. O’Brien & Hope (2010: 7550) observes that “energy systems are a product of many interacting forces including socio-economic factors, resource availability and constraints, technological capacity and political aspirations”. Thus, due to the complex

³ Appendix A. Table A2 the techno-economic data for potential projects

interactions between energy systems and these forces, demand and supply of energy has to be analysed simultaneously so that a balanced system can be developed. In addition to meeting energy demand, supply options have to be financially viable, and both environmentally and socially acceptable. Therefore, to ensure that all critical aspects of an energy system are captured, a process of integrated planning was developed (Eberhard 1992).

In energy planning terms, this integrated approach is referred to as Integrated Energy Planning (IEP). Through IEP, communication links are created between energy supply, demand sectors, macro-economic and socio-economic systems (Eberhard 1992). This enhances the understanding of how best energy can be supplied and/or managed. As EarthLife SA (2005: 1) puts it, the ultimate objective of IEP “is to decide how to meet energy service needs in the most efficient and socially beneficial manner, keeping control of economic cost while serving national imperatives such as job creation and poverty alleviation”. Thus, the product of IEP leads to an appropriate balance between conflicting objectives – economic, environmental and social.

2.6.1. Energy Models

As seen above, energy systems are made up of many characteristics. Thus, to ensure that all of them are accounted for in the planning process, these characteristics have to be integrated into an energy model. A model can be defined as a prototype of something that is real (Sterman 1991; Bisschop 2008). Therefore, an energy model could be defined as a simplified representation that captures essential characteristics of a real energy system.

Aspects that influence the system could be of social, economic and environmental importance. Thus, all useful models are designed around a question that needs to be understood. To help develop a consistent, transparent and error-free model, computer-based models are used. These models are in themselves defined by equations and data to capture underlying relationships between different characteristics as in a real system. A model should be as complex as it needs to be to answer the questions being asked, not more complex (*Occam's Razor*). There is a wide range of modelling options available to end-user/modeller (see Section 3.3 and 3.4.), but the usefulness of each of these options is significantly influenced by the purpose and the level of skill of the end-user/modeller.

The reasons for using models to analyse an energy system have been summarised by Sterman (1991) and Bisschop (2008) below as follows:

1. Construction of models can serve as a learning process: In an attempt to construct a representative model, the modeller is forced to understand the essential characteristics and relationships of the real system so that it is mimicked correctly.
2. Modelling process leads to goal focus: Because of the complexity of the real system, it could be difficult to understand the effect of a specific characteristic. Thus, through modelling, these characteristics can be comprehensively studied.
3. Models could be used as a medium of discussion: With all the modelling assumptions clearly stated, different policy scenarios could be simulated and their outcomes could be used as a basis of discussion between concerned parties.
4. Implication-free outcomes: Some decisions are irreversible and the consequences could be costly. Therefore, by use of models these decisions can be simulated with no effect on the real system.
5. Enables quick outcomes: Due to the computational prowess of computer-models, decisions can be simulated and their effects clearly understood within a short space of time other than having to 'wait for natural process to take its course' (as in the real system that is).
6. Optimisation of the system: Different aspects of a system could be analysed and some process would be improved or even removed while returning the same benefit – this may lead to reduced costs or even increased system profits.
7. Computer-models do not make logical errors: When the objective and all relationships of the model have been correctly defined, the model will consistently and repeatedly analyse the data to that objective.

2.6.2. Energy Security

Energy security has in the recent past become a key issue when designing energy policy and strategies, albeit for different reasons (Helm 2002; Huang and Wu 2008; Nuttall & Manz 2008; Bambawale & Sovacool 2011). Energy Security is normally defined either in terms of a system's ability to provide energy during a sudden shock (short term), or reduction of use of energy sources that would cause sudden shocks (long term). The International Energy Agency (IEA) defines energy security as the ability of an energy system to reliably supply energy at an affordable price while minimising its impact on the environment (IEA 2012). This definition can be further broken down into four aspects: availability of energy, accessibility to energy supply, affordability, and environment needs. Below is a brief description of these aspects.

Availability of energy would be described as having energy and in the right amounts to meet the demand. For instance, a country could have vast coal resources but as long as it is not mined, that energy source is not available for use.

Access to energy supply is having the necessary infrastructure to make the energy available to the end-user. In most developing countries like Zambia, this aspect of energy security is the most essential as there is limited access to modern energy forms.

Affordability is about providing an energy service that would enable the end-user to use it and also support economic growth while being cost reflective.

Environmental needs are about facilitating sustainability while providing the energy services. For instance, while certain energy sources can ensure supply of energy at a lower price, but they may not be ideal if they cause a lot of air pollution or increased GHG emissions.

The complexity of the energy security can be seen from the above description. Therefore, development of an energy-secure system has to be a consented effort by all stakeholders to ensure that these aspects are balanced. This could mean increasing the energy prices from unsustainably low prices to a cost reflective price so that new investments into the system could be supported.

2.6.3. Energy System Diversification

As an old proverb goes ‘do not put all your eggs in one basket’. This is the thinking behind system diversification. However, how to spread these eggs is not as straight forward (Grubb et al. 2006). For example, what could be the best diversification policy for South Africa (which has significant coal resources) would be different to Zambia’s option (which has a significant hydropower potential).

Fossil based energy systems are said to cause climate change, but hydro dominated energy systems are potentially vulnerable to climate variability caused by climate change. Thus, diversification policies and strategies have to be unique to a specific energy system. For instance, some systems would require diversification from imported oil, while others would require diversifying from coal which is a major GHG emitter and causes air pollution.

In that respect, Zambia’s electricity system faces a huge threat from climate variability such as droughts. There is need to diversity the system; notwithstanding the fact that Zambia has considerable untapped hydro potential. System diversification is essential for promotion of sustainable development and energy security (Li 2005; Ebinger & Vergara 2011), because it

minimises the risks of supply disruption shocks on both the economic and energy systems. Therefore, through a diverse system, Zambia could be able to supply power to a wider population (both rural and urban) and also minimise shocks which would be detrimental to the fragile economy. Apart from the benefits of risk reduction of the system, diversifying the system with locally available energy sources would significantly contribute to the local economy (Khatiwada et al. 2012).

Further, diversification policy in this research means increasing the share of non-large hydro plants in the energy mix. Non-large hydro-power includes coal, solar, oil, gas, mini-hydro and bio technologies options. Since least cost strategy for future system expansion are large hydro plants, which are vulnerable to climatic changes, the system planning objective needs to be redefined to include both cost and risk minimization objectives.

There are two main methods that are used when analysing energy system's diversity: Shannon-Weiner and Herfindahl-Hirschmann indices.

2.6.3.1. The Shannon-Weiner Index (SWI)

The SWI is a simplified indicator for measuring diversity, and is dependent on assumptions being made. In this research, diversification was between large hydro versus non-hydro technologies. The index is defined as

$$SWI = \sum -p_i \ln(p_i) \quad \dots 2.1$$

Where,

p_i is the proportion of generation technology type i .

This index can be interpreted as follows: the closer the value is to zero, the more dependent the system is on one technology type and vice versa.

2.6.3.2. The Herfindahl-Hirschmann Index (HHI)

The HHI works quite the opposite of the SWI, the larger the indicator the less diversified the system is. In most cases where this index has been used, the analyses were centred on market competition. The index is defined as

$$HHI = \sum p_i^2 \quad \dots 2.2$$

Where,

p_i is the percentage share of the technology type i .

2.6.4. Demand Side Management

Demand Side Management (DSM) considers options of how electricity usage can be altered and in many cases reduced. If DSM measures are successfully implemented, they could bring with them a lot of benefits such as delayed capacity development (due to reduced demand or peak demand), increased economic efficiency, and reduced GHG emissions. Gellings (1985: 1468) defines a DSM as

“the planning, implementation, and monitoring of distribution network utility activities designed to influence customer use of electricity in ways that will produce desired changes in the load shape, i.e. changes in the time pattern and magnitude of the network load”.

There are six ways in which electricity demand can be managed: Peak Clipping; Valley Filling; Load Shifting; Strategic conservation; Strategic load growth; and Flexible load shape (Gellings 1985; Qureshi et al. 2011). Zambia’s electricity system is currently facing challenges with peak loads, and with projected increase in electricity demand, strategic conservation and strategic load growth would be of great importance. Therefore, to maximise the utilisation of the electricity system, it is important that DSM opportunities are identified and implemented.

2.7. Technology Options for Electricity System Expansion in Zambia

Globally, there are many different technologies that can be used to generate electricity, such as solar, wind, nuclear, geothermal, gas, hydro, coal, oil, and bio technologies. Nevertheless, not all these technologies are possibilities for electricity generation in Zambia by 2030. Among them only hydro, solar photovoltaic (PV), concentrated solar power, geothermal, gas, oil, coal, and bio technologies have been identified as viable for electricity generation between now and 2030.

2.7.1. Hydro technology

As mentioned earlier, almost 100% of Zambia’s electricity is generated from hydro technologies. There is currently about 1 889 MW of hydro installed and about 6 000 MW untapped potential.

The major downside to this technology is its vulnerability to climate variability, as was experienced in 1991/92 season and the potential threat from climate change. However, the Zambia and Southern Africa Power Pool (SAPP) have put emphasis on developing

hydropower because it offers a least cost energy system path for Zambia and also could help in reducing the GHG emissions in the SADC region.

2.7.2. Solar Photovoltaic technology

This is the fastest growing electricity generation technology in the world. It offers a good option for enhancing supplies to rural areas that are isolated from grid electricity. This technology is currently being used in Zambia's rural areas (Ellegard et al. 2004; Haanyika 2008) albeit at a small scale. However, if the right policies and institutional frameworks are put in place, this technology offers one of the best options of diversifying from hydropower.

The downsides of this technology, among others, are variability in electricity output and high investment costs. Firstly, as Sims et al. (2003) observed that solar PV cannot be relied on to provide power as needed due to their intermittence of power output. Secondly, the penetration of this technology in Zambia has been significantly hampered by the high investment cost (Sims et al. 2003; Haanyika 2008; Lemaine 2009).

2.7.3. Concentrated Solar Power Technology

This technology is also referred to as solar-thermal power. Globally, installed capacity stands at about 400 MW. There are increasing interests in developing the technology for more power generation (RSA 2010; Bazmi and Zahedi 2011).

However, because the technology is still under development, the uncertainty over the future costs of investment possesses a great challenge to its development. Thus, the future uncertainty of the technology together with human resources development needs and the requirement of large land area would hamper the development of this technology in Zambia.

2.7.4. Geothermal Technology

There are a number of potential sites for geothermal projects in Zambia. Documented geothermal potential is about 50 MW (UNESCO/USAID 1982). However, none of this potential has been harnessed for electricity production due to its lack of economy of scale.

2.7.5. Gas Technology

There is about 80 MW of gas turbine installed capacity in Zambia, owned by CEC. These installations are for emergency back-up for mining firms (ERB 2008). However, due to the high cost of gas importation, these installations have not been operated for a long while now.

Therefore, the most viable way to further develop this technology is by building importation infrastructure such as a gas pipeline from Angola or Namibia or Mozambique. However, for this to come to fruition, it would take a long time and the author is of the view that the possibility for such to happen would be after almost all the hydropower potential has been harnessed. Further, developing gas technologies in Zambia also entails increase in energy security risks since the fuel would be imported (unless links to several suppliers were developed). Thus, infrastructure investment capital requirements, GHG emissions concerns and energy security concerns would significantly challenge the large scale development of gas technology for electricity production in Zambia.

2.7.6. Oil Technology

There is about 10 MW of installed capacity in Zambia. As mentioned earlier, these installations were meant to be used for base-load provision in isolated areas. However, as expected, it has proven to be very costly to operate these plants because of the high costs of fuel. There are, however, plans to build a 50 MW heavy fuel oil (HFO) power plant which would be operated as a peaking plant in Ndola (ERB 2012).

There are three main challenges to development of oil technology in Zambia. These are the uncertainty attached to fuel price, GHG emissions and the energy security concerns. Apart from future price uncertainty, oil technologies could also face a threat from carbon policies.

2.7.7. Coal Technology

There are proposals to develop coal power plants for electricity production in Zambia. Diversification of the electricity system and stimulation of local economy have been the primary drivers for this development proposal. Based on the coal reserves and processing infrastructure, Zambia can build and operate more than 2 000 MW of coal power plant capacity.

However, the two main disadvantages of coal development are the air pollution and high GHG emissions. Therefore, the threat of carbon policies on the technology is significant.

2.7.8. Bio technology

Production of electricity from commercial bio-fuels such as bagasse would easily be supported in Zambia since there is already a developed sugar industry in the country. Currently, there is limited use of bagasse from the sugar industry – mainly for thermal heat generation within the industry.

Large scale development for electricity production from bagasse would be enhanced by the growth in the sugar industry, as this would require considerable amounts of bagasse. This development would also require the investment into bagasse handling infrastructure. Despite these requirements, bio technology would offer a base-load plant option which is carbon-free and cost effective.

2.8. Climate Variability and Project Change in Southern Africa

Climate change is a broad and highly contested topic, and in some circles, it is considered a fallacy. The IPCC defines it as a persistent change in the mean and /or variability of climate properties over a relatively long period of time i.e. decades; while the UNFCCC defines it as the change in climate that is as a result of human activities which increase GHG, such as carbon oxide, methane and nitrous oxides, in the atmosphere that causes change in climate system's equilibrium composition (IPCC 2007). The UNFCCC definition is narrowed down in line with its objectives – to mitigate the climate change due to human activities. However, regardless of the position or definition that one adopts, climate change could pose a serious threat to human and natural systems.

Since the 1800s, the concentration of carbon dioxide (CO₂) in the atmosphere has been on the rise, from 280 ppm in 1800 to 350 ppm in the early 2000s. This can be traced to the industrial revolution of the early 1800s which depended on fossil fuels. To date, the world's energy system still depends heavily on fossil fuels, and this trend looks set to continue into the future if nothing is done. This has raised international concerns, as GHG causes the greenhouse effect. Greenhouse effect is a phenomenon which develops when the concentration of GHG increases in the atmosphere and forms a layer that absorbs the long-wave radiations from the atmosphere and reflects them to the earth's surface. This further leads to an increase in the earth's surface temperature, and thus the equilibrium state of the global climate system alters. This leads to a process known today as anthropogenic climate change (Klein et al 2005; Schwartz 2008). There are, however, other natural causes to climate change. Nevertheless, such causes are not within our immediate powers to stop.

From the time of industrial revolution to date, global temperature has increased by about $0.74^{\circ}\text{C} \pm 0.18^{\circ}\text{C}$ (Klein et al 2005; Schwartz 2008; IEA 2010). This suggests a relationship between increase in the GHG and temperature rise. This warming trend would have significant implications such as change in rainfall patterns, increase in health problems,

change variability occurrences, loss of bio-diversity and reduction in water for hydro power plants. The latter implication is of main interest to this research study.

2.8.1. Climate Variability

The IPCC (2012a) defines climate variability as the “variations in mean state and other statistics (such as standard deviations and the occurrence of extremes) of the climate on all temporal and spatial scales beyond that of individual weather events”. These variations could be influenced by internal climatic system processes or induced by external factors (IPCC 2012a) which could manifest in form droughts, floods or extremes in temperatures.

Southern Africa has been a victim of climate variations, with Kandji et al. (2006) observing that it poses a big challenge to food security and general economy in this region. These variations are closely linked to the El Nino-Southern Oscillation (ENSO). ENSO are oceanic occurrences that affect the sea surface temperature, wind flow and precipitation patterns. For instance, during a warm ENSO occurrence, there are generally dry conditions over southern Africa (Richard et al. 2001).

Increased ENSO occurrences in southern Africa have resulted in an increase in the surface temperature (Kandji et al. 2006) and increased inter-annual variability in rainfall (Richard et al. 2001). Richard et al. (2001) also observes that even though there was increased inter-annual variance in rainfall in the 20th century, there was minimal changes in the rainfall patterns. However, the future rainfall patterns remain uncertain.

Studies by Ragab & Prudhomme (2002) and Kandji et al. (2006) observed a consistently increasing warming trend in the region in the past few decades and also reduction in total rainfall. These observations could have serious future implications on the region’s economic and hydropower projects. During the 1991/92 drought, the Zambian government lost US\$300 million in drought costs while Zimbabwe’s GDP fell by 11% (Kandji et al. 2006). There was also a reduction in electricity generation of 8% at the Kariba Dam plants in that same period (Mukheibir 2007). This clearly suggests that climate variability possesses a serious challenge to energy security from hydropower technologies in southern Africa, and particularly Zambia which is over 99% reliant on hydro technologies for electricity production.

2.8.2. Climate Change Projections

Based on the simulation of two regional climate models (RCMs), MM5 and PRECIS models, Tadross et al. (2005) projects that southern African climate will experience change. There will be changes in the rain days, total summer season rainfall, and average surface

temperature. These models were downscaled to 10 years of control and 10 years of future climate. Control period for MM5 model was 1975-1984 while 1970-1979 was used for PRECIS. The models were then simulated within the constraints of IPCC emissions scenario A2. Emissions scenario A2, describes a situation of growing regional integration with high economic development. Under this scenario, the world development is very heterogeneous.

The models show that the increasing trend in mean temperature will continue through to 2070-2079 period and so will the reduction in total summer (October-March) rainfall. These results are within 90% confidence level. Over Zambia, the results show that there will be increased temperature and increased total rainfall during October-December period, but during January-March period, the country would experience lower mean temperature and total rainfall. These results are within 95% and above confidence interval. (Tadross et al. 2005) These findings are consistent with the studies by Ragab & Prudhomme (2002), Harrison and Whittington (2002) and Arnell (2004). Thus, even though there remains a lot of uncertainty on how climate will change in the region, the trend suggests that the climate in the region will get hotter and drier.

Being an inland country, Zambia's mean temperature is expected to increase by 3 – 5 °C by 2070 (Tadross et al. 2005; Mukheibir 2007). This would lead to an increase in evaporation from the rivers and lakes, which in turn could affect the production of hydropower from these water bodies. Further, Arnell (2004) urges that with or without climate change, water stress in southern Africa is projected to increase. Therefore, planning of an energy system that is hydropower dominated has to be carefully thought through.

There are four major ways in which climate change can affect hydropower projects as summarised by Mukheibir (2007): increased evaporation, reduced run-off due to droughts, increased run-off due to floods, and siltation.

2.8.2.1. Increased Evaporation

Surface evaporation is the major threat of water resources loss from a hydropower facility (Mukheibir 2007). As surface temperature increases, the heat causes water to be lost to the atmosphere. Thus, as the rivers run through Zambia's hot and dry valleys, the amount of water which was supposed to go to hydropower production would be lost to the environment. Further, WCD study (2000) observes that evaporation is a major threat to the Kariba Dam facility. Kariba Dam houses a facility of 1 470 MW (with considerable potential for additional power plant installations) and has a water body of 180.6 cubic kilometres. Lake Kariba loses about 1500 mm per year of water due to evaporation, and the average rainfall in the southern

part of Zambia (where Lake Kariba is located) is about 500 mm per year (WCD 2000; GRZ 2008).

2.8.2.2.Reduced Run-off due to Droughts

After a drought, run-off water is drastically reduced. This could further be affected by increased withdrawal of water for irrigation and other human consumption needs. The impacts of drought are immediately felt on the run-of-river type of hydropower plants. However, depending on the length of the drought, plants with reservoirs could also be affected; for instance the 1991/92 drought which affected the Kariba Dam plants (Mukheibir 2007).

The WCD (2000) observes that climate change would reduce inflow by about 10-50% into Lake Kariba. Further, WCD study indicates that a 20-30% reduction of inflows would adversely affect the production of electricity.

2.8.2.3.Increased Run-off due to floods

Floods are just as undesirable as droughts. The study by Tadross et al. (2005) projects an increase in rainfall intensity; this could in turn enhance the frequency of flood occurrences (Mukheibir 2007). Floods could cause mud-slides and also cause objects to block the inlet points of water into the power plant facility. This could impact the plant operations; as was the case for Kafue Gorge power plants in 2005 (MEWD 2007). Floods could also reduce the effective generation capacity of the power plant.

2.8.2.4.Siltation

“Siltation [sic] refers to the deposition of particles of the river load” (Mukheibir 2007: 8). As the climate changes, so will the soil erosion patterns. Thus, due to inconsistent water flows of the river (varying from dry low flows to wet flooding flows) different sizes of soil particles would be carried along and deposited in the plant facilities. This would over time reduce the lifespan of the plant.

2.8.3. Climate Resilient System

Climate has had significant negative⁴ impacts on energy systems globally, and this is expected to continue if nothing is done. Energy systems, more notably the hydropower dominated systems, have been affected through various forms of climate variability. Thus, there is

⁴ There are of course positive impacts, but the focus in this research was how the negative impacts of climate can be minimised.

currently a lot of thought given to how such systems can be made more resilient. A resilient system will ensure reliable energy supply, which would in turn encourage development. Therefore, to develop a climate resilient system, technologies that are not vulnerable to climate should be preferred over those that are.

An energy resilient system is one that “exhibit adaptive capacity to cope with and respond to disruptions by minimising vulnerabilities and exploiting beneficial opportunities through socio-technical co-evolution” (O’Brien & Hope 2011: 7551). In this case, a resilient system would be the one that is less vulnerable to climatic changes.

2.9. Technology Learning for Renewable Energy Technologies

There has been significant reduction in the cost of investment in various RE technologies (Winkler et al 2009). This cost reduction movement has mainly been due to two factors: learning-by-doing and economies of scale. Learning-by-doing entails that better, cheaper and quicker methods have been developed for producing these technologies over time. Secondly, due to increased demand of these technologies, manufacturers have been able to produce massive quantities, which enable them to profitably operate their businesses even when the technologies are sold at a relatively lower price. Even though most of RE technologies are currently expensive compared to other electricity generation technologies (Nemet 2006; Winkler et al. 2009), their cost could become very competitive as more of them are being installed in the future.

Based on observed cost movements, this reduction in the cost (learning) is frequently modelled using the log-linear function for its simplicity and best fit as summarised by Nemet (2006).

$$C_t = C_o * (Q)^{-\epsilon} \quad \dots 2.3$$

$$PR = 2^{-\epsilon} \quad \dots 2.4$$

$$LR = (1-PR) \quad \dots 2.5$$

Where,

C_t is the unit cost of a technology per installed capacity (\$/kW) at time t ,

C_o is a initial cost of the technology (\$/kW),

Q is cumulative installed capacity ratio of technology over time,

ε is the learning coefficient,

PR is the progress ratio which is the measure of learning, and

LR is the learning ratio (decreasing percent rate).

2.10. Carbon Policies

Since the energy sector is a major contributor to GHG emissions, different mitigation and adaptation responses have been proposed (UNFCCC 2007). Mitigation responses focus on prevention of climate change and future climate impacts by deliberately dealing with its causes while adaptation responses look at how best humanity and environment can adapt to the changing climate. Both types of these responses are necessary. However, this section focuses on how carbon policy (a mitigation measure) can be used to reduce GHG emissions.

A carbon policy is a market-based policy instrument that is charged on every carbon emitted into the atmosphere. Thus, the policy targets technologies that emit carbon while acting as an incentive to those that do not emit. Carbon policies can further encourage efficient utilisation of energy due to increase in energy cost in those systems that are dominated by carbon-emitting technologies (Shrestha et al 1998; Zhenxiang et al 2011; Zhixin & Ya 2011).

This study however, only focuses on how the policy can act as a supply-side substitution mechanism where usage of gas, oil and coal technologies (for electricity generation) becomes less competitive to the available cleaner technologies such as solar, bio-fuels and hydropower.

Notwithstanding its perceived effectiveness, carbon policies are not yet obligatory but there is a possibility that not long from now they would become a reality in many nations

2.11. Electricity System Expansion Considerations

Developing an electricity system expansion plan is a complex process. This is because there are many parameters that have to be quantified and many of them are uncertain. Uncertainties of whether the future demand will be within the limits of the projections or whether the technologies being proposed will be appropriate to supply future electricity demands still remain. Despite these uncertainties a system expansion plan has to be developed because of the long lead time that is required before a power plant becomes operational. A country's failure to develop a reliable energy system well in advance could adversely affect both its economic and social sectors to a point of collapse.

Therefore, to develop a cost effective, robust and flexible electricity system, a number of factors have to be considered. These factors, among others, include the knowledge of demand and its shape; desired reliability; and economic, technical, sustainability, and human resources constraints.

2.11.1. Demand Profile

In order to develop an expansion plan, it is important to have knowledge of how much electricity will be needed and at what times because electricity cannot be stored cheaply. This knowledge will help in deciding what type of plants to develop – base-, intermediate- or peak-load plants.

By combining daily load profiles and then rearranging the demand in a descending order of magnitude, a Load Duration Curve (LDC) can be developed. The LDC shows the “cumulative frequency distribution of system loads” (IAEA 1984: 122). The LDC is then plotted with the system load (in MW) on the vertical axis and time during which the load occurs in the horizontal axis. The area underneath the curve gives an idea of what capacity would be needed at what period of time. Therefore, the shape of the LDC could then be used to decide what types of plants are required and therefore, the generation mix. Figure 2.10 below shows a LDC for Zambia’s secondary electricity demand in 2008.

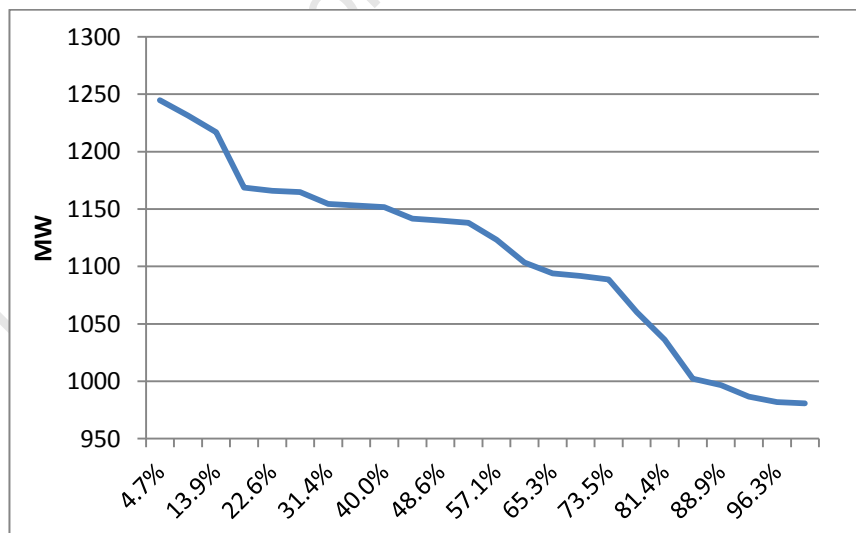


Figure 2.10 Load duration curve for secondary electricity in 2008 (based on author’s analysis)

Depending on the fluctuations in demand, a generation mix would be made up of the base-, intermediate- and peak-load plants. Base-load is the minimum electrical energy that is required by the end-user at any particular time of the day and does not change significantly over time. However, intermediate- and peak-loads fluctuate depending on the time of day,

season and weather conditions (Nicholson et al. 2011). Hence, it is critical to know which technologies could be used for what loads when developing an optimal generation mix.

The base-load plants provide power to meet demand requirements in a continuous and cost effective way over a period of time, in this case a year. Peak-load plants on the other hand, provide power during peak periods; these plants are expensive to operate and thus, it is more economical to use them for short periods only. Intermediate-load plants are the bridge between base-load and peak-load plants both in terms of operations and construction costs. Examples of base-load plants are coal, nuclear, bio, and hydropower plants. These plants are operated for longer periods (above 60% of the time) for power production and generally have long start-up time (except for hydropower). Intermediate-load plants are operated within 30-60% of the time; while peak-load plants only run for shorter periods (less than 30% of the time). Further, peak-load plants have low investment costs and short start-up time, but are very high operation costs. Examples of intermediate-load plants are hydropower plants, solar, wind, while peak-load plants would be gas and oil plants.

2.11.2. Desired Reliability

System reliability is the ability of an electricity system to provide power to meet demand within acceptable quality standards (Munasinghe 1981; Makarov & Moharari 1999). Reliability can be broken down into two attributes, adequacy and security. Adequacy measures the ability of a system to meet the aggregate energy demand while security measures the ability to withstand sudden shocks (Makarov & Moharari 1991). There are two broad approaches used when measuring system reliability: deterministic and probabilistic indices.

Deterministic indices are fairly simple calculations and require little data. Indicators such as reserve margin, largest generation unit and dry year are used. These measures are usually established and benchmarked over time. Probabilistic indices are mathematically rigorous methods that include various factors that influence system reliability (Makarov and Moharari 1999). Factor such as Loss of Loss Probability (LOLP); Loss of Load Hours (LOLH); Loss of Load Expectation (LOLE); and Excepted Un-served Energy (EUE).

2.11.3. Constraints

Regardless of the viability of technology type, there are a number of constraints that have to be considered when developing the energy system. These constraints could be technical, economic, environmental and human resources. Thus, depending on the challenges or opportunities these constraints offer, an optimal generation mix could be developed.

2.11.3.1. Technical Constraints

Under this constraint, technology characteristics such as start-up, shut-down, availability and reliability are considered. Coal and nuclear technologies take long to start-up and also to shut-down; therefore, they are only suitable for base-load provision. However, oil and gas technologies could be used for peak-load due to their ability to ramp up production within a short time (Ramana & Kumar 2009). On the other hand, since Zambia’s system is predominately hydropower based, run-of-river type of plants could be scheduled for dispatch first followed by plants with reservoirs. This would ensure that the technologies are maximised because plants with reservoirs could be operated more flexibly.

2.11.3.2. Economic Constraints

Generation technologies such as nuclear, coal, and large hydropower involve huge capital investment, but they tend to be cheaper (in \$/MWh terms) when operated at full capacity. Thus, such technologies are better suited for base-load type of operation. Even though technologies such as the reservoir hydro plants could be used for peak-load provision, this option could lead to a high electricity generation costs due to the limited time with which the plants are operated.

Generation costs for technologies such as gas-turbines and diesel-generators (that have relatively lower investment costs) are significantly influenced by the operation costs such as fuel cost (as shown in figure 2.11 below). Thus, if these plants are operated as peak-load plants, the generation cost would be moderately low due to the limited time of operation.

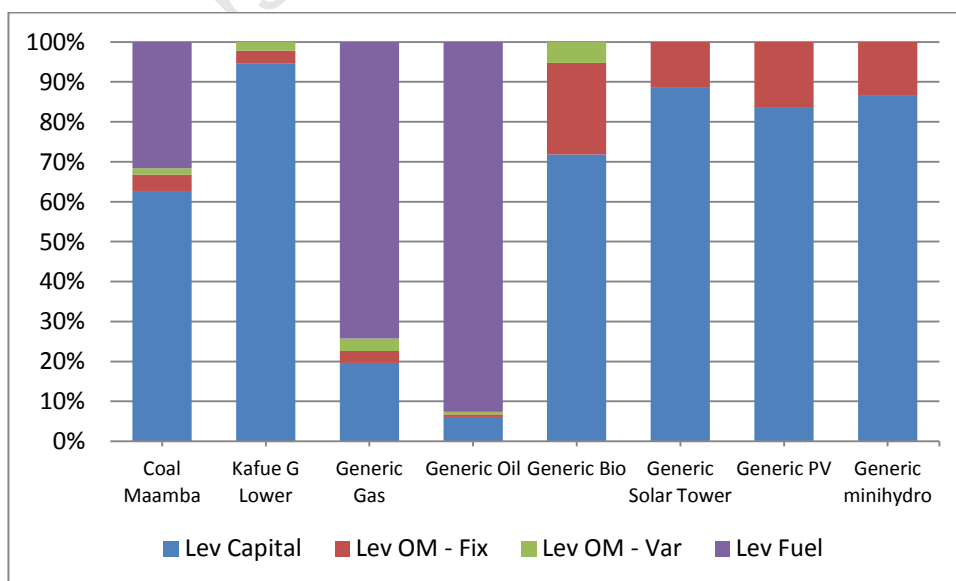


Figure 2.11 Stacked costs of generating electricity in 2008 for selected technologies (based on author’s analysis)

2.11.3.3. Sustainability Constraints

Globally, there are increasing concerns surrounding environmental and societal acceptance of certain technologies due to their effects on bio-diversity, risk of accidents, air pollution and GHG emissions. Thus, even if a technology type qualifies under the technical and economic constraints, a country may not develop that technology due to its undesirable sustainability characteristics. Further, the future profitability of GHG emitting technologies is uncertain with the possible introduction of carbon policies. For instance, even though coal technologies could have a lower generation cost than RE technologies, introducing a carbon policy could make RE technologies competitive due to the increase in coal technology's generation costs. Thus, the uncertainties over possible future environmental regulations and instruments have to be taken into consideration when developing an energy expansion plan.

2.11.3.4. Human Resources Constraints

Like in any other project development, human resource is a major factor in its success. Depending on the desired direction of electricity system development, human resources development programs have to be developed and implemented. This is an essential part of success of any development process, as was the case in South Korea's nuclear energy programme (Choi et al. 2009). Thus, increasing a share of technology supply should be done with respect to available local human resource capacity. Further, this means that technologies should not suddenly be brought online instead they should be gradually developed as human resource capacity is also being developed.

2.12. Sustainability Issues

Concerns over the increase of GHG emissions into the atmosphere from the energy sector are well documented in literature (UNFCCC 2001; IPCC 2007). Any energy system expansion process should take into account that the proposed expansion plan does not worsen the situation. However, because of other developmental challenges faced by most developing countries (Zambia included) there must be a balance between developing of a reliable energy system and minimising GHG emissions (Ellis 2007; Herz 2007; Reddy and Assenza 2009). This brings in the concept of sustainable development. The Brundtland Commission defines sustainable development as "development that meets the need of the present without comprising the ability of future generations to meet their own needs" (IAEA 2005: 1). From this definition and as explained above, it is clear that Zambia's energy system has to be able to meet the present electricity needs. Currently, the system is not providing sufficient electricity which is essential in promoting sustainable development. As Nkomo (2007) observes there is a strong linkage between energy use and economic development. However,

in securing energy supply for the present generation, the impacts on future generations should be within tolerable limits.

Further, increase in energy supply could encourage electrification, as there would be electricity to supply. Increased accessibility could further enhance wider participation (both from urban and rural populations) in national development (Haanyika 2008; GRZ 2011) and also improve the livelihood of the people (Vera & Langlois 2007; Khatiwada et al. 2012).

2.13. Emerging Issues

The review of literature shows that there is an agreement that hydropower dominated electricity systems are vulnerable to climate variability such as droughts. Further, the literature reviewed showed that there are high possibilities that climate variability occurrences will increase in Zambia with the advent of climate change. Furthermore, the impact of the variations in water availability on the cost of electricity generation has not been fully understood in Zambia's electricity system. Therefore, detailed analysis will have to be carried out on how the system can be made climate resilient within reasonable limits of generating costs.

A climate resilient path may entail increasing investments into solar, coal, gas, oil, and bio technologies. However, there are also some uncertainties attached to these technologies which have to be addressed. Therefore, by developing an energy system model, these uncertainties can be analysed. This can be done by exploring plausible future development scenarios that contain these uncertainties.

3. Modelling of Zambia's Electricity System

3.1. Introduction

This chapter gives a detailed description of the steps that were taken to develop both the Demand Side and the Supply Side models. However, due to limited availability of data, the Demand Side model was only developed at a final energy demand level for each sector. The energy demand projections output from this model were then used as exogenous inputs into the Supply Side model. In developing the Supply Side model, a number of assumptions were made as explained in Section 3.6.2. A detailed technology generation model was developed as it was the main focus of the research, while the models for the transmission and distribution networks were not detailed.

The sections below give details of the steps taken and all the assumptions made.

3.2. Time Horizon

This study covered a period of 22 years, from 2008 (base year) to 2030 (end year). For both Demand Side and Supply Side models, time slices of one year were used throughout the analysis period.

In the Supply Side model, each time slice was further broken down into twelve (12) seasons (i.e. monthly seasons) to facilitate a more accurate representation. Each season was represented by one day-type, 'Anyday'. The day-type was further divided into four load regions.

3.3. Modelling Frameworks

There are three main modelling frameworks: simulation, accounting, and optimisation frameworks (Gitrakos et al. 2009). Depending on the purpose of the model that needs to be built, a particular framework can be used. Below is a description of each of these model frameworks.

3.3.1. Simulation Models

Simulation models are descriptive tools. They enable the user/modeller to have a deeper understanding of how altering a variable (such as policy instrument) would affect the behaviour of the other system characteristics (such as energy consumption patterns). In other words, these models are used to answer 'what if' type of questions.

These types of models have two main components, “a representation of the problem being studied and a set of decision-making rules” (Alfstad 2005: 44). The methodology in these models is highly complex and abstract (Giatrakos et al. 2009). Therefore, the user/modeller has to be highly skilled to use them effectively. An example of a simulation model is Energy 20/20.

3.3.2. Accounting Models

Accounting models are a particular form of simulation modelling framework. However, instead of simulating the behaviour of the system, accounting models give the user/modeller a specific outcome based on the input assumption and data. Accounting models feature “simple, transplant and flexible interface with lower data requirements” (Giatrakos et al. 2009: 1224). These models do not require the user/modeller to be highly skilled. Examples of accounting frameworks are LEAP and MEDEE/MEAD.

3.3.3. Optimisation Models

Optimisation models are mostly used for finding an optimal solution based on the set objective within the given options. Depending on the objective, such as to minimise CO₂ emission from the energy sector or to maximise profits from a particular service being provided, optimisation models will prescribe to the user/modeller what needs to be done to achieve the target. This framework is used as a prescriptive tool.

Optimisation models can be classified into three broad categories: linear, integer and non-linear programming models (Bisschop 2008). Most of the common models used in energy modelling optimisation are linear programming tools (Howells n.d; Bisschop 2008); tools such as MARKAL, TIMES, MESSAGE, and IPM. Linear programming is a method “where the objective function and constraints are linear” (Alfstad 2005: 38). Bisschop (2008) formulates a general linear model as

$$\text{Minimise: } \sum_{j \in J} (c_j x_j) \quad \dots 3.1$$

$$\text{Subject to: } \sum_{j \in J} (a_{ij} x_j) \geq \text{or} \leq b_i \quad \forall i \in I \quad \dots 3.2$$

$$x_j \geq 0 \quad \forall j \in J$$

Where,

C_j s are cost coefficients,

a_{ij} s are constraint coefficients, and

b_i s are requirements.

However, if a function is to be maximised, the above ‘minimise’ equation is multiplied by ‘-1’. Equation 3.1 in this case is the objective function while equation 3.2 represents the constraints.

Different methods can be used to calculate for the optimal solution. The optimal solution from these linear energy models have to be further tested for robustness since models are just prototypes and may not capture all the characteristics that could influence the real system. Sensitivity analyses could be used to investigate the stability of the solution. The stability of the solution can be investigated by varying the coefficients to check for changes in the solution. If the change is not significant then the solution is valid.

Notwithstanding their usefulness, optimisation models are not suitable for non-quantitative analysis and require a considerable level of skill and data from the user/modeller.

3.4. Modelling Tools

Two energy models and Excel spreadsheet were used to model and analyse Zambia’s electricity system. Long-range Energy Alternative Planning system (LEAP) was used to model the demand side, while Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) was used to model the supply side system. Excel spreadsheet was used mainly for further processing and analysing of the models’ output.

3.4.1. Long-range Energy Alternative Planning System (LEAP)

There are many models that can be used to forecast energy demand. However, Bhattacharyya & Timilsina (2010) argues that LEAP and MEDEE/MEAD are better suited to capture complex characteristics in developing countries’ energy system because of their flexibility.

LEAP is a “scenario-based energy-environment modelling tool” (Heaps 2010: 1). This energy model was developed through collaborative work between Stockholm Environment Institute – Boston (SEI –Boston) and five other leading institutions: the Energy Research

Centre, formerly Energy and Development Research Centre, University of Cape Town; the ETC Foundation, the Netherlands; the Regional Wood Energy Development Programme of the Food and Agriculture Organisation, Asia; the Institute for Energy Economics of the Fundacion Bariloche, Argentina; and the Environment Development Action in the Third World, Senegal. LEAP has evolved over time into a model that can be used to “build sophisticated simulation and data structures” (Heaps 2010: 1). For this research, the model was only used to perform energy projections functions. LEAP was chosen as it is adequate to model the demand side of the Zambian system given the problem at hand, the time and the data available.

3.4.2. Model for Energy Supply Strategy Alternative and their General Environmental Impacts (MESSAGE)

MESSAGE is an optimisation systems engineering model which was originally developed by IIASA. This tool is used for medium- to long-term energy planning, policy analysis, and scenario development. The data management structure in MESSAGE allows for development of relationships from energy resources level through to end-user energy demand level. MESSAGE can be generally categorised as a dynamic linear model, although it also has a mixed integer option (IAEA 2007; IIASA 2012).

MESSAGE uses the energy demand projections from accounting models (in this case LEAP). Energy demand projections and techno-economic data are then integrated into the MESSAGE platform to build an energy system model. This model is then run to find an optimal solution of how energy demand can be met. The solution is based on the available supply options and the constraints defined by the user/modeller.

3.5. Demand Side Modelling (Projections)

Zambia has in the recent past seen an increase in electricity demand. This increase has also led the previously enjoyed system surplus into deficits (ERB 2008). This could mainly be attributed to the surge in economic activities. These activities are expected to continue increasing (GRZ 2011). Therefore, there is urgent need to develop models that can be used to inform decision-makers on possible future development scenarios. These models could play an important role in ensuring that supply infrastructure investment and other initiatives’ (such as energy management initiatives) decisions are made in good time. Timely decision making would be cardinal to the continuous economic development of the country, since energy use and the economy are still heavily linked.

To develop a clearer picture of energy demand, the energy system demand was divided into four sectors (residential, agricultural, services and industrial) and the future demand was then projected on that basis. Description of what each sector includes can be found in the Section 3.5.2.

Between 2000 and 2010, Zambia's GDP grew at an average annual rate of 5.69%. The total real GDP in 2008, 2009 and 2010 was \$15 818.1, \$16 831.0 and \$18 111.8 million (2005 US\$ constant price ppp) respectively (BoZ 2010; World Bank 2011). The contribution to GDP by these sectors in 2010 is as shown in figure 3.1 below.

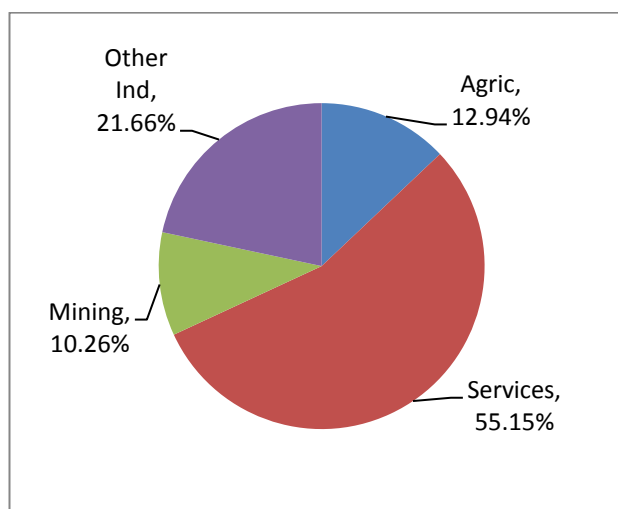


Figure 3.1 Sector contributions to GDP in 2010 (based on author analysis)

3.5.1. Research Design

This section (Demand Side model) of the research was designed to develop a baseline of the current energy usage and then project the electricity demand based on the stated assumptions. The main sources of data were reports published by the Government of the Republic of Zambia (GRZ), Energy Regulation Board of Zambia (ERB), Bank of Zambia (BoZ) and World Bank. The data from World Bank was mainly used for comparisons with other countries, such as South Africa as shown in Section 3.5.6.

This method of data collection was considered appropriate as these publications are trusted and also reflect the state of affairs in the country such as policy direction. Data that was required to build the model was readily available in these reports and suitable to develop the model at a final energy demand level.

3.5.2. Introduction to sectors

Generally, the sectors were divided into two types, Economic and social categories. The economic category consists of agricultural, services and industrial sectors while residential sector was the only one under the social category.

It should be noted that fluctuations in electricity intensity (kWh/\$) between 2006 and 2009 as shown in Tables 3.1 – 3.4 is mainly because of movements in commodity prices during that period.

3.5.2.1. Industrial Sector

This sector is the largest consumer of final electricity demand in Zambia and a major foreign exchange earner. The sector consists of activities such as mining, quarrying, construction, manufacturing, pulp & paper and other related activities (BoZ 2009). The electricity consumption is dominated by the mining and quarry sub-sector, which is electricity intensive, and it was for this reason that the industrial sector was further divided into mining & quarry and Other Industries.

In this sector, physical output and value added are the main drivers for electricity demand. End-use demands are directed towards compressed air, processing, thermal, motive, HVAC and other utilities. Therefore, as industrial processes such as mineral beneficiation increase, the demand for energy increases.

Most of the energy services are supplied by electricity, with boiler fuels coming from electricity, coal and various liquid oil products.

3.5.2.1.1 Mining & Quarry

This sub-sector is the economic backbone of Zambia. It contributes over 70% of all the foreign exchange earnings (GRZ 2011) and consumes over 50% of the final electricity demand⁵ (ERB 2008). However, it only contributed about nine (9%) percent to the total GDP⁶ in 2008 (BoZ 2009), making it an electricity intensive sub-sector per GDP output. Table 3.1 shows the energy intensity (kWh/\$ ppp 2005 constant price) of this sub-sector from 2006 to 2009. It can also be noticed from the tables (Tables 3.1 and 3.2) below that there was a sharp decrease in electricity intensity (kWh/\$) between 2007 and 2009 mainly because of the global increase in copper price during that period.

⁵ Appendix B, Table B1 Final electricity consumption balance

⁶ Appendix B, Table B2 GDP contribution per sector

Table 3.1: Electricity Intensity in Mining & Quarry sub-sector

	2006	2007	2008	2009
Electricity Intensity (kWh/\$)	3.3912	3.8386	2.9972	2.6464

3.5.2.1.2 Other Industries

Other Industries include all industrial activities except for the mining & quarry sub-sector. This group of sub-sectors are not electricity intensive nor are they a major consumer of final electricity, consuming only about seven (7%) per cent (ERB 2008). However, their contribution to GDP is significant (BoZ 2009), contributing slightly over twenty one (21%) per cent. Table 3.2 shows the energy intensity (kWh/\$ ppp 2005 constant price) of this sub-sector from 2006 to 2009.

Table 3.2: Electricity Intensity in Other Industries sub-sectors

	2006	2007	2008	2009
Electricity Intensity (kWh/\$)	0.6168	0.1585	0.1413	0.1412

3.5.2.2. Agricultural

The agricultural sector is the largest employer in Zambia, employing about 69% of the total workforce (CSO 2005). It consists of all activities in agriculture, fisheries and forestry sub-sectors.

It is a significant contributor to the total GDP (about nineteen per cent) but its electricity consumption is low (ERB 2008; BoZ 2009). This could mainly be attributed to low levels of mechanization, as most activities are at subsistence level. Hence, there is considerable amount of latent demand, that is, an increase in mechanization would see a large leap in electricity demand per unit GDP output.

Much of the electricity in this sector is directed towards thermal purposes, processing, irrigation, harvesting & packing, and other energy uses. Therefore, depending on the level of modernisation and development of the sector in future, energy demand could increase considerably. Table 3.3 below shows the energy intensity (kWh/\$ ppp 2005 constant price) of this sector from 2006 to 2009.

Table 3.3: Energy Intensity in the Agriculture sector

	2006	2007	2008	2009
Electricity Intensity (kWh/\$)	0.0434	0.0928	0.0812	0.0802

3.5.2.3. Services

The services sector includes social services, commerce and transport sub-sectors, and is the largest contributor to the total GDP. This sector consists of activities such as trade, hospitality, community services, property, transportation, finances, personal services, communications, and other similar activities. It consumes slightly above nine (9%) per cent of the total electricity and accounts for over 50% of the total GDP (ERB 2008; BoZ 2009).

The main end-uses of energy in this sector go towards heating, space conditioning, lighting and other utilities. Therefore, growth in the floor space area or occupancy of a given activity would require more energy directed to these end-uses. However, because of lack of information of both floor space and occupancy in Zambia, GDP output was used to calculate projected demand. Table 3.4 shows the energy intensity (kWh/\$ ppp 2005 constant price) of this sector from 2006 to 2009.

Table 3.4: Electricity Intensity in the Services sector

	2006	2007	2008	2009
Electricity Intensity (kWh/\$)	0.0934	0.0766	0.0751	0.0766

3.5.2.4. Residential

This sector is the social base of Zambia. Electricity demand in this sector is mainly driven by household (HH) income and population or HH growth. It has been observed (Mdluli 2007; Howells 2008) that an increase in HH income increases the consumer's preference for modern fuels such as Liquefied Petroleum Gas (LPG) and electricity. Thus, depending on the future economic outcome, demand for electricity might reduce or increase. On the other hand, growth in connected population or HH will inevitably increase the demand for energy.

Most of the electricity demands in the sector go towards water heating, lighting, cooking, appliances and space conditioning.

Data on consumption patterns for the residential sector was difficult to find, therefore residential demand was only considered at an aggregate level, that is, there was no Rural-Urban split. Figure 3.3 below shows the electricity intensity per household and also that of GDP/household changes in Zambia's residential sector from 2001 to 2008.

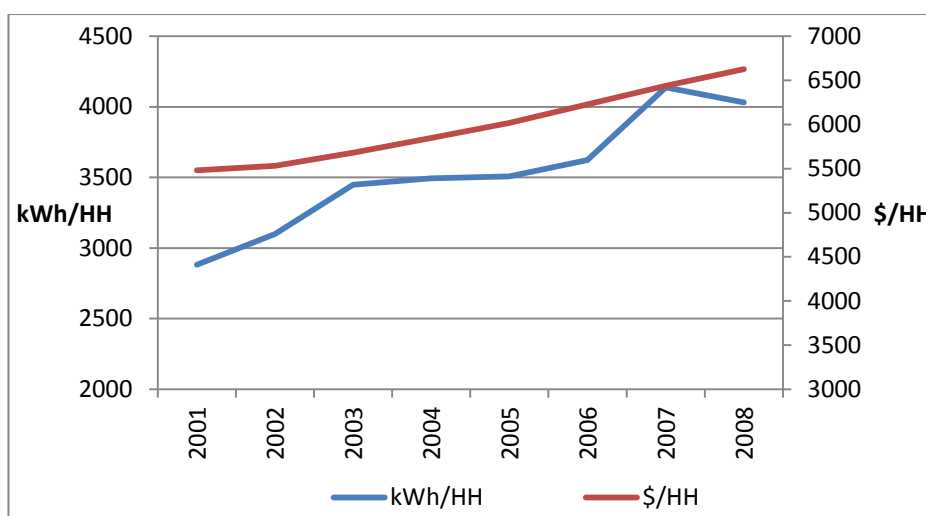


Figure 3.2 Graphs of electricity intensity and GDP/Household in Zambia

3.5.3. General Assumptions

Below are the general assumptions that were made, it was assumed that:

- The population⁷ in 2008, 2009 and 2010 was 12 412 093, 12 745 844 and 13 088 750 people respectively (World Populations Prospects 2012). However, from 2010 to 2030, a population annual growth rate of 3.15% was assumed (MFNP 2010). The growth rate is an average of High fertility and Low fertility population scenario projections which also takes effects of HIV/AIDS into account. It was further assumed that the household (HH) size was 5.2 (CSO 2005) and did not change throughout the analysis period.
- The urbanisation trend would continue, and by 2030, 49.6% of the population would have settled in urban areas from 2008's 39% (CSO 2011). It should, however, be noted that from 1980 to 2000 Zambia had experienced 'ruralisation' (CSO 2003).
- Without electrification policy intervention, only 34% of the population will have access to electricity by 2030. Conversely, with electrification policy intervention (EPI), access to electricity in rural areas would be improved from the current 3.2% to 15% by 2015 and 50% by 2030. With a total national accessibility of 66% by 2030

⁷ Appendix C, Table C1 Population and Household projections

(GRZ 2008). Further, only High and Base-Case EPI Growth paths' residential projections were based on the policy intervention.

- From 2010 to 2030, the total GDP annual growth rate was 3.5%, 6.42% and 9.14% for Low, Base-Case and High Growth paths respectively. During this period, sectorial growth rates were as shown in Table 3.5 below.

Table 3.5 Economic assumptions for each development scenario

Sector/Scenario	Low-Growth		Base-Case		High-Growth	
	2010-19	2020-30	2010-19	2020-30	2010-19	2020-30
Overall Growth Rate	3.50%		6.42%		9.14%	
Services	3.20%		6.41%		8.80%	
Agriculture	6.50%		6.40%		7.80%	
Industrial						
Mining & Quarry	1.10%	0.50%	6.00%	5.10%	11.30%	4.60%
Other Industrial	3.30%	2.40%	6.60%	7.00%	9.70%	12.20%

3.5.4. Scenarios

During the late 1960s & early 1970s, there was increased activity in the Zambia's mining & quarry sub-sector to meet global demand for copper and other mining products. This led to the building of Kariba North Bank and Kafue Gorge Power stations to supply the mines (WCD 2000; IMF 2008). But the need for power was short lived when the copper demand drastically dropped, which further caused an economic downturn for Zambia, leading to surplus in electricity supply.

Today, Zambia is faced with a similar challenge to that of the late 1960s and early 1970s, the need to meet increasing electricity demand. Zambia's economy is heavily dependent on the mining & quarry sub-sector. This suggests that a stable electricity supply to the mining & quarry sub-sector is essential for economic growth and also stable operations in this sub-sector would further promote full utilisation of the available power. Three economic scenarios⁸ were considered to project future demand: Low-Growth (LG), Base-Case (BC) and High-Growth (HG) scenarios.

3.5.4.1. Base-Case

Under BC scenario, it is assumed that all sectors grow albeit at a lower rate. There is limited growth in the mining & quarry sub-sector due to lack of supporting infrastructure. The GDP

⁸ Appendix C, Table C2 Economic projections per sector

structure remains almost the same as that of 2010; with a growth rate of 6.42% between 2011 and 2030. This growth rate is an average of 2006-2010 period.

3.5.4.2. Low-Growth

Under this development scenario, it is assumed that the economy slowed down from 7.4% growth rate in 2010 to 3.5% from 2011 to 2030. The emphasis in this scenario turns to the agricultural sector as the demand for copper and other mining products reduce. The services sector remains the main contributor to GDP while agricultural sector increases its contribution to GDP.

3.5.4.3. High-Growth

This is an optimist scenario that considers high growth in all sectors (agricultural, services and industrial) albeit at different rates. Much of the growth comes from the industrial sector, which was heavily supported by the growth in the mining & quarry sub-sector. The scenario assumes that there is consistent increase in the demand for copper and other mining products, and that Zambia keeps expanding her industrial activities to meet the demand. The GDP growth rate of 9.14% is assumed from 2011 to 2030. This scenario represents a preferred development path which leads to Zambia becoming a middle income industrialised country by 2030 as described in Vision 2030 (GRZ 2006).

3.5.5. Modelling Approach

To meet future demand, it is essential that each sector's consumption needs are comprehensively modelled based on the possible futures. This is critical, because it would provide insight on the growth of demand and hence help in deciding what resources and type of supply technologies to develop. Also, because of the nature of investment that is demanded for power plants, it would be useful to have an idea of the possible demand so that finances and other systems could be put in place well in advance. Therefore, planners should use appropriate methods and tools when projecting energy demand to avoid future shortage or excess in capacity, as was the case in Indonesia (Rachmatullah et al. 2007).

There are two main approaches that are used to project future energy demand: top-down and bottom-up. The decision of which approach to use is dependent on the purpose of the model (IPCC 2012b). The top-down approach is based on the assumption that the economy is well developed and relies heavily on historical data. The bottom-up approach is more suitable for developing economies since it can capture other energy usage outside the economy (ESD 2007; Bhattacharyya & Timilsina 2010). The top-down and bottom-up approaches are

commonly represented by the Econometric and End-Use Engineering models respectively (Swan & Ugursal 2009; Suganthi & Samuel 2012).

3.5.5.1. Top-down Approach

These are aggregate models depicting the interaction of the economic and energy systems (mainly focusing on commercial energy forms). Top-down models are developed using historical economic data and its relationship to the dependent variable, energy. Future projections are tied to past trends. This coupling to past trends makes it difficult to capture structural changes in the economy and technology improvements that take place over the long term (Swan & Ugursal 2009; Suganthi & Samuel 2012).

The most commonly used method in this approach is an Econometric method (Sharma et al. 2002; ZhiDong 2003; Pokharel 2007), in form of a static Cobb-Douglas function as shown below;

$$ER = aY^{\alpha}P^{\beta} \quad \dots 3.3$$

Where,

ER is the Energy Required,

a is a coefficient,

Y is the Gross Domestic Product (GDP),

P is the Electricity Price, and

α and β are elasticity factors GDP and Electricity Price respectively.

The major drawback of using this method for energy projection in Zambia is that the country's economy is still developing. Therefore, some of the energy consumption outside the economy cannot be accounted for.

3.5.5.2. Bottom-Up Approach

This type of model builds up sectorial demand from an end-use level. Contrary to the top-down model, it requires considerable detailed data, such as energy consumption and technology improvements data. Therefore, this approach takes into account energy consumption reduction gained due to improvements in a technology's efficiency.

The two commonly used methodologies in this approach are statistical and engineering end-use methods (Swan & Urgusal 2009).

Of these two methods, engineering end-use method was applied to carry out electricity demand projections because of its suitability as explained below. Firstly, End-Use method gives the flexibility of carrying out detailed sectorial analyses. Secondly, End-Use makes it possible to identify improvement opportunities as all the technology details can be explicitly considered. Thirdly, this method doesn't heavily depend on historical data, thus creating a baseline can easily be done. This further avoids future demand trend from being tied to the past as is the case in Econometric models (ESD 2007; Swan & Urgusul 2009).

Below is a general equation that was developed for this research, expressing energy required as a function of activity multiplied by energy intensity. It should be noted however, that all demand projections were done at a sectorial final energy demand level as categorised in Section 3.5.2.

$$ER = \sum A * E \quad \dots 3.4$$

Where,

ER is the Energy Required,

A is the Activity demanding energy (such as number of electrified households, floor space, GDP output and industrial output), and

E is the electricity Intensity.

3.5.6. Residential Sector Projections

The residential sector has unique features from all other sectors. It is the social face of the nation and could be looked at as a consuming sector that does not directly contribute to economic growth.

As mentioned earlier, apart from the number of households connected to electricity supply, income plays a significant role on how households use electricity. However, since data for household income was not available, GDP/capita was used as a proxy. This was to show the effect that increase in income could have on electricity demand.

Thus, equation 3.4 was transformed into

$$ER_t = A_t * E_o * (1 + \epsilon)^{(t-2008)} \quad \dots 3.5$$

Where,

A_t is the number of households with access to electricity in year t,

E is the electricity Intensity, which increases with increase in income per household,

E_0 is the base year intensity, and

ε is the elasticity between electricity intensity (kWh/HH) and income (GDP/HH) in this case.

$$\varepsilon = \left(\frac{\left(\frac{E_{SA} - E_0}{IH_{SA} - IH_0} \right) * (IH_{2030} - IH_0) + E_0}{E_0} \right)^{\left(\frac{1}{2030 - 2008} \right)} - 1 \quad \dots 3.6$$

Where,

IH_0 is the HH income in the base year,

E_{SA} and IH_{SA} are the average (1980-1989) values of South Africa.

The electricity intensity (E_0) is an average of residential electricity consumption divided by electrified household for the years 2006, 2007 and 2008. It was assumed that with increase in income, more households were transiting from using traditional fuels to more convenient forms of energy such as electricity. Also, other already connected household tended to increase the utilisation of electricity thus, increasing the intensity per household.

It is assumed that the elasticity followed the path of South Africa, since it was calculated based on the UN data of Energy Intensity per capita versus GDP per capita of South Africa. It is further assumed that the elasticity follows a linear path as shown in equation 3.6. South Africa data was used for three main reasons, firstly because South Africa and Zambia are in the same region (Southern Africa). Secondly, they are both mineral rich countries, and lastly, the data was available. The elasticity was calculated based on the US\$ Purchasing Power Parity (ppp) 2005 constant price as provided by the World Bank dataset. This made the comparison of the two countries much easier. It should also be mentioned that a linear regression of Zambia's energy and economic data (data from 1973 to 2007) was performed but it was found that the results were not significant. This could be due to the fact that Zambia's economic markets are still developing and the economic-energy system cannot appropriately capture these characteristics.

3.5.7. Economic Sectors Projections

Projections for all economic sectors were done by multiplying Energy Intensity (which was calculated as kWh/US\$) and GDP (US\$ contributed by the respective sector). The intensity calculations were an average of 2008 and 2009 and GDP projection were based on the economic growth projection as shown in Table 3.5. It was further assumed that intensity does not change throughout the analysis period.

Thus, using equation 3.4, total energy demand from the economic sector was,

$$ER_t = (A_t * E_t)_{\text{Mining}} + (A_t * E_t)_{\text{Oth Ind}} + (A_t * E_t)_{\text{Agric}} + (A_t * E_t)_{\text{Services}} \dots 3.7$$

3.6. Supply Side Modelling

This section of the thesis focused on developing the electricity supply system of Zambia. The Reference Energy System (RES) was developed for the current installed capacity, and later more technologies were added as demand increased. This section was the main focus of the research. Below are the steps that were undertaken to develop the supply model.

3.6.1. Research Design

Like in the Demand Side section, the data was collected from published sources. Technical and economic data was mainly based on the study that was carried out by SAPP (Nexant 2007). This was a regional study of all Southern Africa Power Pool Utilities. The main aim of the SAPP study was for the development of regional supply and transmission strategies such as promoting trade. Thus, individual countries were not studied in detailed. Nonetheless, this study built a rich database of technical information from all the utility companies in the region. Further, information from this study was checked against that in the GRZ and ERB publications to ensure that the information is up to date and where information was dated it was replaced by the latest available information. Other sources were consulted such as technical reports (DHEC 2012) of upcoming projects.

Data such as technology learning, fossil fuel prices, electricity import prices, transmission lines cost, and emission factors were collected from various publications, as compiled in the Appendix A (Table A3, A4, A5, A6 and A7).

3.6.2. General Assumptions

The following are the general assumption for the supply model:

- All monetary values used were adjusted to a common year - 2008.
- The planning period was from 2009 to 2030.
- The reference constant discount rate was 10%, the effects of changing discount rate are considered in Section 3.6.4.
- Reserve Margin was used as a measure of system reliability, as it is also the current practise within SAPP. A reserve margin (RM) of 15% was maintained throughout the

analysis period. However, it should be noted that most SAPP reports use RM of 10.2%. But because Zambia's electricity system is hydropower dominated, the RM of 15% was preferred.

- The fossil fuel prices would take the Current Policy path as in World Energy Outlook (IEA 2010).
- Only solar, mini and bio technologies have exogenous technology learning, and the optimistic price projections (IEA 2008; RSA 2010) were used.
- The future cost of imported electricity would take the path as projected in RSA (2010).
- Only residential, services, and agricultural sectors had varying load profiles⁹ and curves, while for industrial sector, they were constant.
- The transmission and distribution losses and costs were constant throughout the analysis period.
- The overall transmission and distribution losses were taken to be 3.5% and 20.74% respectively.
- The general transmission network and the distribution lines into the industrial sector had the same percent losses (3.5%).
- The cost¹⁰ of distribution losses (i.e. \$/kWh) between industrial and Other (services, residential, and agriculture) had a ratio of 1: 6. This assumption was based on the presentation by Roussouw (2010).

3.6.3. Investment Cost Analysis

Expansion of the electricity generation system calls for careful planning both in operational and financial sense. Further, developing a reliable electricity system demands long lead time and requires considerable amounts of finances. In order to carry out a comprehensive investment planning analysis, mathematical tools are used. These tools take different forms, they could be linear or non-linear, or stochastic or deterministic (Pokharel & Ponnambalam 1997).

There are different methods that would be used to compare available options for system expansion with respect to their costs. The most common method is the Levelised Cost of Electricity (LCoE) (Ramana & Kumar 2009; IEA/NEA 2010). LCoE assumes a constant discount rate and electricity price over the economic life of the technology. This method is

⁹ Appendix A, Table A8 Load profiles for 'Other' demand

¹⁰ Appendix A, Table A9 Transmission and Distribution network costs

suitable for monopolised and regulated systems (IEA/NEA 2010). It was for this reason that it was appropriate to use in the Zambian electricity system expansion analysis.

3.6.3.1. Time Value of Money

Investing in the electricity system happens at different times, as need arises. The value of money will therefore be different from time to time. Thus, in order to compare different technology options that might be needed at different points in time, the changes in the value of money over time have to be accounted for. This can be done by levelling the monetary value to the same base year. A mathematical process called Present Value Analysis (PVA) can be used to develop this baseline, i.e. by compounding or discounting of the values to a common point. IAEA (1984) observes that PVA is more useful to regulated markets, like Zambia's.

One important central assumption in the PVA is the discount rate. The IAEA (1984: 133) defines discount rate “as the rate of interest reflecting the time value of money that is used to convert benefits and costs occurring at different times to equivalent values at a common time”. There are two form discount rates, constant and current. In simplified PVA, as in this research, constant discount rate is used. This avoids the uncertainties and therefore complexity of inflation rate that come with usage of a current discount rate. It should also be noted that developing countries use substantially higher discount rates than developed countries. This is so as “to reflect both the scarcity of capital and the much larger profitability of new investment projects that compete for limited financial resources” (IAEA 1984:133).

The focus of the research was to compare different technology options over their economic life time, thus, the uniform sinking fund formula (IAEA 1984) was of primary focus. It was assumed that investment and operation costs were recovered by the end of economic life of the fully utilised technology. IAEA (1984) summarises the formula as shown in equation 3.8 below:

$$TER_t = TCC_t * \frac{(i*(1+i)^N)}{(1+i)^N - 1} \quad \dots \quad 3.8$$

Where,

TER is the total electricity revenue in year t (TER is constant throughout the analysis period),

TCC is the total cost required to product the electricity during the operation on the technology,

i is the interest rate (in this case, it is the same as the discount rate), and

N is the economic life of the technology (in years).

3.6.3.2. Total Investment Capital Expense Calculations

Total investment costs include all incurred expenses in the process of construction of a power plant. These expenses include overnight costs, interest during construction (IDC), owner's costs, spare parts costs, and other related expenses. However, apart from the overnight cost, interest accrued was of major concern. Thus, for the purposes of this research, it was assumed that total investment cost was only made up of overnight cost and interest accrued.

In order to calculate the IDC, the expenditure schedule of the project had to be known. The expenditure schedules were based on the S-Curves¹¹ used in the RSA (2010). The expenses in each year are expressed in terms of percentages. Therefore,

$$IDC = \text{Overnight Costs} * \sum(((1 + i)^1 - 1) * \mu_1 + \dots + ((1 + i)^x - 1) * \mu_t) \dots 3.9$$

Where,

i is the interest rate (in this case, the same as the discount rate),

μ is the percentage share of capital expended in year t.

$$\text{Total Investment Costs} = \text{Overnight Costs} + IDC \dots 3.10$$

3.6.3.3. Technology Levelised Cost of Electricity Supply Calculations

After establishing a general baseline for all technology cost as described above, the LCoE can then be calculated for each technology. As,

$$LCoE_{\text{gen costs}} (\$/MWh) =$$

$$\frac{\text{Total discounted costs accrued in the generation of electricity by the technology}}{\text{Total discounted electricity generated by the technology}} \dots 3.11$$

Where,

the total generation costs is made up of total capital investment costs, fixed operations and maintenance costs, variable operations and maintenance costs, fuel costs, and carbon costs.

Equation 3.11 can be further broken down into segments;

$$LCoE_{\text{capital costs}} = \sum \frac{CRF * \text{Capital Cost per kW} (\$/kW)}{CF * 8760} \dots 3.12$$

¹¹ Appendix D, Table D1 Project S-Curves

Where,

CF is the plant availability in a year,

The year is represented by the number of hours – 8760 hours.

CRF is the capital recovery factor, and defined as;

$$CRF = \frac{d*(1+d)^N}{(1+d)^N - 1} \quad \dots 3.13$$

Where,

d is the constant discount rate,

N is the economic life of the technology in years.

$$LCoE_{\text{fixed O\&M costs}} = \sum \frac{\text{fixed O \& M Costs per kW (\$/kW)}}{CF*8760} \quad \dots 3.14$$

$$LCoE_{\text{variable O\&M costs}} = \sum \frac{\text{variable O \& M Costs (\$)}}{\text{Electricity Generated (MWh)}} \quad \dots 3.15$$

$$LCoE_{\text{fuel costs}} = \sum \frac{\text{fuel costs (\$)}}{\text{Electricity Generated (MWh)}} \quad \dots 3.16$$

$$LCoE_{\text{carbon costs}} = \sum \frac{\text{Carbon Price per tonne of fuel (\$/tonne)}}{\text{Electricity Generated per tonne of fuel (MWh/tonne)}} \quad \dots 3.17$$

Thus, equation 3.11 can be re-written as,

$$LCoE_{\text{gen costs}} = LCoE_{\text{cap costs}} + LCoE_{\text{fixed O\&M costs}} + LCoE_{\text{var O\&M costs}} + LCoE_{\text{fuel costs}} + LCoE_{\text{carbon costs}} \quad \dots 3.11a.$$

Transmission and Distribution (T&D) Costs can be calculated in the same way as the generation LCoE shown above. However, it was assumed that both the transmission and distribution networks only had variable O&M costs (see Section 3.6.2).

Thus, T&D costs and LostElec costs can be calculated as summarised below by Ramana & Kumar (2009):

$$LCoE_{\text{T\&D costs}} = \frac{\text{Total cost accrued to transport electricity (\$)}}{\text{Total electricity transported (MWh)}} \quad \dots 3.18$$

$$LCoE_{\text{LostElec costs}} = LCoE_{\text{gen costs}} \left(\frac{1}{(1-\text{TransLoss\%})*(1-\text{DistrLoss\%})} - 1 \right) \quad \dots 3.19$$

Therefore, in order to compare technologies (centralised and distributed), the total levelised costs for electricity¹² supply of each technology can be calculated by adding outcomes of equations 3.11a, 3.18 and 3.19. (Note: it was assumed that distributed technologies have no T&D and LostElec costs). Thus,

$$LCoE_{\text{TotaldelElec cost}} = LCoE_{\text{gen cost}} + LCoE_{\text{T\&D cost}} + LCoE_{\text{LostElec cost}} \dots 3.20$$

3.6.4. Scenarios

Scenarios are developed to explore plausible futures. The focus of the research was to investigate the effects of the dry year on the average cost of electricity generation and also to explore other avenues of how the electricity system can be made resilient to dry years. To effectively analyse the system, two climatic scenarios (average and dry year) were considered. Further, average year only considered least cost system for all the three demand scenarios, while dry year considered a system with and without a diversification policy (for only Base-Case and High Growth).

To check the stability of the optimal solutions, a total of five sensitivity tests were applied to scenario DY2 and DT2 (these scenarios are described in Table 3.6 and 3.7 respectively). The sensitivity parameters that were adjusted are discount rates (6% & 14%), carbon price (\$ 25 & \$ 50 per tonne) and pessimistic learning for RE technologies.

3.6.4.1. Reference scenario

Reference scenario assumed that throughout the analysis period, the river flow is normal (average year), with varying costs of import electricity and fossil fuel. Electricity trade was limited to 355 and 195 GWh for exports and imports respectively. Under this scenario, all the three (LG, BC and HG) demand projections were run. This scenario offers least cost development option for the energy system for all the growth scenarios.

3.6.4.2. Least Cost Dry Year scenario

This scenario assumed dry year across all river systems in Zambia except on mini hydropower plants, starting from 2016 up to 2030. The dry year scenario investigated the impacts that reduced river flow could have on the system. Based on the outcome of the Reference scenario, hydropower projects that came online were then ‘fixed’ – both in capacity and timing. Hydropower projects were ‘fixed’ to reflect the limited knowledge that decision-makers have

¹² Appendix D, Table D2 Total LCoE for all the supply technologies

about future climatic changes. There were three other variations (as shown in Table 3.6) of dry year, DY, DY2 and DY3.

Table 3.6 Least cost dry year scenarios

	Scenario Name		
	DY	DY2	DY3
Policy Parameters			
Objective	Least Cost	Least Cost	Least Cost
Import Limit	Max. of 22.23 MW from 2009 to 2030	Max. of 22.23 MW from 2009 to 2030	22.23 MW (2009-12) then 2060 MW (2013-30)
Sensitivity Parameters			
Hydro Availability	Dry year	Dry year	Dry year
Demand	Base-Case	High Demand	High Demand

3.6.4.3. Diversification dry year scenarios

This scenario explored how the energy system would respond to a dry year if there was a deliberate policy to diversify the system before dry year. Diversification implementation would start from 2016 through to 2030. No technology was ‘fixed’ in this scenario. Diversification in this case, was any technology development away from large hydropower. This scenario had three other variations, DT1, DT2 and DT3, as described in Table 3.7

Table 3.7 Scenarios under Diversification Dry year option

	Scenario Name		
	DT1	DT2	DT3
Policy Parameters			
Objective	Diversify to 15% by 2030	Diversify to 15% by 2030	Diversify to 15% by 2030
Import Limit	Max. of 22.23 MW from 2009 to 2030	Max. of 22.23 MW from 2009 to 2030	22.23 MW (2009-12) then 2060 MW (2013-30)
Sensitivity Parameters			
Hydro Availability	Dry year	Dry year	Dry year
Demand	Base-Case	High Demand	High Demand

The equation 3.21 shown below was used when calculating the minimum level of diversification into the system. Diversification of the system was done gradually.

$$y(E_{nlh}) \geq x(E_{nlh} + E_{lh})$$

... 3.21

$$x > 0$$

Where,

E_{nlh} is the electricity produced from non large hydro power technologies,

$(E_{nlh} + E_{lh})$ is the total electricity being produced by electricity system,

y is a coefficient (in this case $y = 1$), and

x is the target percentage of non large hydro technologies to be introduced into the system at a set time.

3.6.5. Model Simulation

A detailed model was developed based on the collected data using MESSAGE software.

Different scenarios were run and results were exported to Excel for further analyses.

The figure below shows a schematic flow chart of the simulation process:

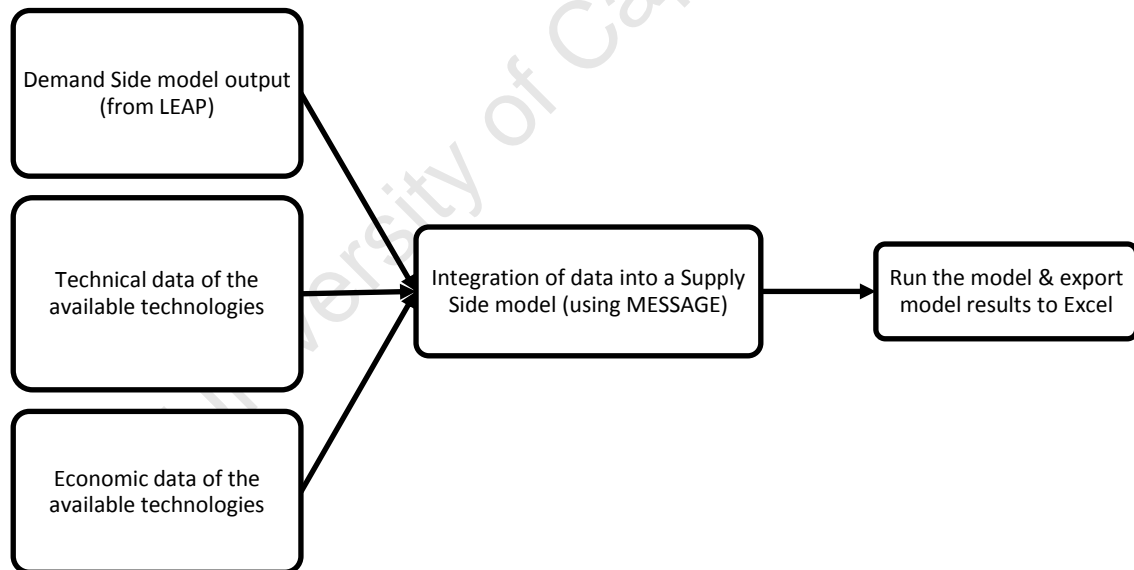


Fig 3.3 Schematic diagram of Supply modelling flow chart

The results were as presented in the following chapter.

4. Results and Discussion

4.1. Introduction

This chapter presents and discusses the results of the models (both Demand Side and Supply Side models) as described in Chapter 3. The Demand Side results are presented for all the three demand scenarios (BC, LG and HG scenarios) according to sectors. Results for the Supply Side are presented based on the two climatic scenarios – average and dry year river-flows. The first part of the chapter presents the results of development growth scenarios in an average year. The following part then focuses on the HG system in a dry year scenario. The system is analysed with and without a diversification policy so that impacts of a dry year can be better understood. Role of trade policy in a dry year is also discussed. Indicators such as average generating cost, required capital investment and CO₂ emissions are analysed and presented for the least cost and diversified systems. A number of different sensitivity tests are carried out to analyse the stability of the solution. Lastly, based on the analysis, an electricity expansion plan is proposed.

4.2. Demand Side Model Results

4.2.1. Electricity Demand Projections

Based on the economic and population projections, electricity projections were done. The Electricity-GDP/household elasticity (ϵ) was then calculated, based on the GDP and HH projections. The LG, BC and HG scenarios' elasticity were 0.000526, 0.003338 and 0.007365 respectively. The final electricity demand projections for each growth scenario are as shown in Table 4.1 below.

Table 4.1 Final electricity demand projections (in GWh)

	Low Growth	Base-Case	Base-Case + EPI	High Growth
2010	7 128	7 128	7 128	7 128
2013	9 679	10 651	11 270	12 457
2016	10 483	12 662	13 955	16 964
2019	11 377	15 054	17 001	22 754
2022	12 316	17 647	20 482	27 575
2025	13 370	20 688	24 721	33 487
2030	15 431	26 973	33 964	46 553

Electricity demands for the LG scenario will increase by a factor 2.2 in 2030 relative to 2008. The largest increase in demand is in the HG scenario, which increases by a factor 6.5. Nevertheless, if the economic structure remains the same and follows the BC scenario, the electricity demand is expected to increase by a factor of 3.8. The difference in final electricity demand between the HG and the LG scenarios is 31 123 GWh in 2030. This suggests that there is high uncertainty of how demand will evolve. On one hand, Zambia would experience crippling shortages in electricity supply if the economy follows a HG scenario yet the electricity system is designed for LG or BC growth scenario. However, Zambia could also experience excess in power supply if the electricity system is designed for HG scenario and only for the economy to take LG or BC scenario. Therefore, it is imperative that a robust and flexible electricity system is developed. It is also essential that a feedback link between economic and energy system is developed, this would be critical in aiding decision making.

Table 4.1 also shows projections for BC+EPI scenario; this scenario takes the economic projections of BC and GRZ electrification policy targets. Nonetheless, it was assumed that these electrification targets can only be achieved through HG scenario. Therefore, both LG and BC growth scenarios assumed that electrification would continue growing at the current annual rate of 2.1%.

Further, a comparison between BC and BC+EPI, suggests that electrification rate has more influence on the growth of electricity consumption in the residential sector than increase in income per HH. Therefore, the electrification policies could have a significant impact on electricity consumption by the residential sector.

Sector contributions to total electricity demand are shown in Table 4.2 below. In all the growth scenarios, it can be observed that industrial and residential sectors continue to dominate electricity demand. Low growth scenario projects an increase in electricity consumption by the residential sector from 28.4% (in 2008) to 40.6% (in 2030). This is because the contribution of the industrial sector reduces over time. Nevertheless, if the economy follows a LG scenario, rate of electrification could actually slow down because Zambia may face challenges in securing funds for electrification activities.

Table 4.2 Share of sectors' contributions to final electricity demand

	2008	2010	2013	2016	2019	2020	2025	2030
Low Growth								
Agric	0.023	0.021	0.024	0.026	0.029	0.033	0.037	0.043
Services	0.096	0.085	0.086	0.087	0.088	0.090	0.091	0.092
Mining & Quarry	0.529	0.585	0.560	0.533	0.506	0.476	0.446	0.395
Other Ind	0.069	0.062	0.063	0.064	0.065	0.065	0.064	0.063
Residential	0.284	0.247	0.267	0.289	0.311	0.336	0.362	0.406
Base-Case								
Agric	0.023	0.021	0.021	0.022	0.022	0.023	0.023	0.024
Services	0.096	0.085	0.086	0.087	0.088	0.090	0.093	0.097
Mining & Quarry	0.529	0.585	0.586	0.588	0.589	0.583	0.578	0.568
Other Ind	0.069	0.062	0.063	0.064	0.066	0.069	0.072	0.077
Residential	0.284	0.248	0.244	0.240	0.236	0.235	0.234	0.233
Base-Case + EPI								
Agric	0.023	0.021	0.020	0.020	0.020	0.020	0.020	0.019
Services	0.096	0.083	0.081	0.079	0.078	0.078	0.078	0.077
Mining & Quarry	0.529	0.574	0.554	0.533	0.521	0.503	0.484	0.451
Other Ind	0.069	0.061	0.060	0.058	0.058	0.059	0.060	0.061
Residential	0.284	0.262	0.285	0.310	0.323	0.341	0.359	0.391
High Growth								
Agric	0.023	0.021	0.019	0.017	0.016	0.017	0.018	0.018
Services	0.096	0.083	0.078	0.074	0.071	0.076	0.080	0.087
Mining & Quarry	0.529	0.573	0.581	0.588	0.604	0.574	0.542	0.486
Other Ind	0.069	0.061	0.059	0.057	0.056	0.066	0.077	0.097
Residential	0.284	0.263	0.263	0.263	0.252	0.268	0.284	0.312

4.3. Supply Side Model Results

4.3.1. Levelised Cost of Electricity¹³

Hydropower continues to be the cheaper supply option (both in average and dry year scenarios) as shown in Figure 4.1 below. Further, because oil and gas plants have low capital investment cost, it could be cost effective to operate them as peaking plants.

¹³ See Appendix A for the input data

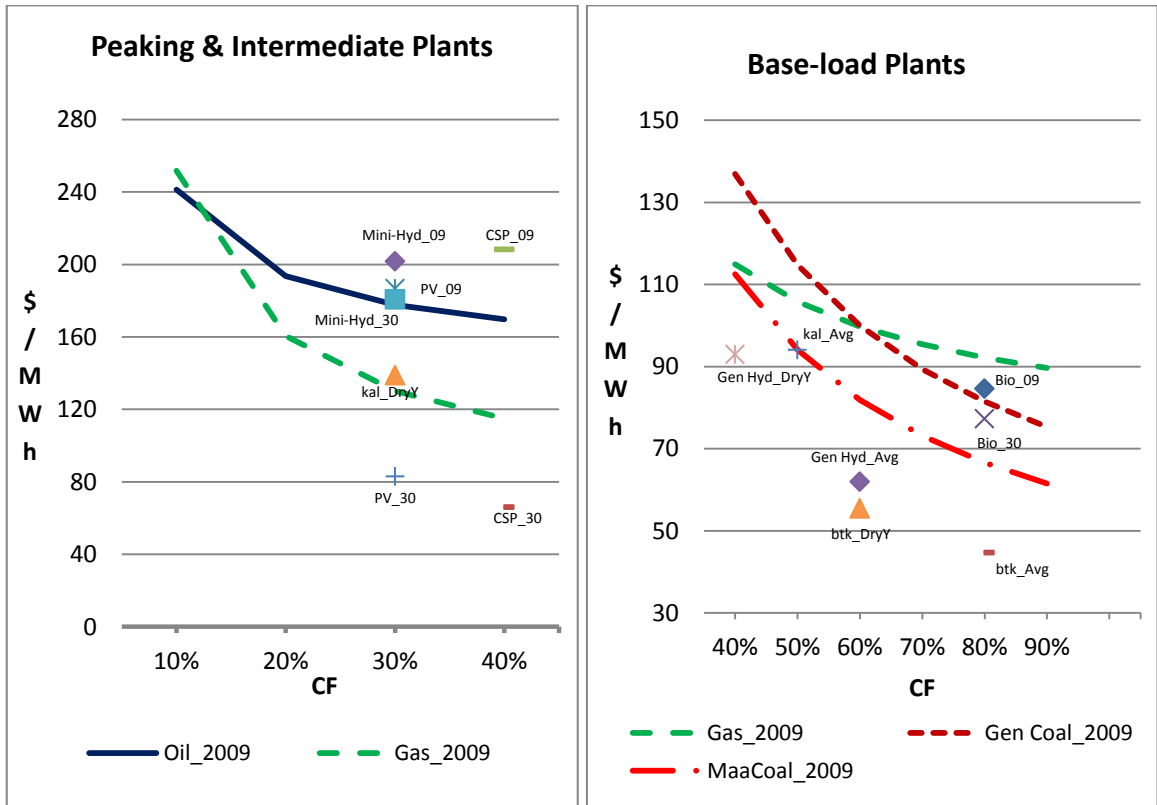


Figure 4.1 LCoE (\$/MWh) for possible supply technologies

With technology learning, RE technologies become competitive option for electricity generation as shown in both figure 4.1 (above) and 4.2 (below).

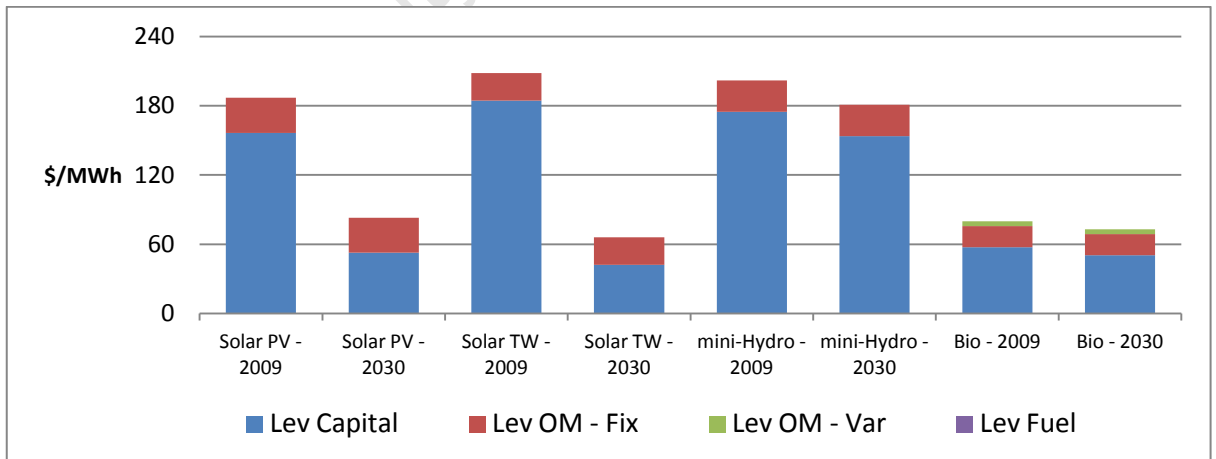


Figure 4.2 LCoE (\$/MWh) for RE technologies

4.3.2. Optimisation Model Results

4.3.2.1. Capacity development for Base-Case demand in an average year scenario

In an average year scenario, required installed capacity is expected to increase from 1 719 MW (2009) to 5 961 MW (2030) in order to meet the BC demand as shown in figure 4.3 below. This capacity installation also represents the least cost system for Zambia.

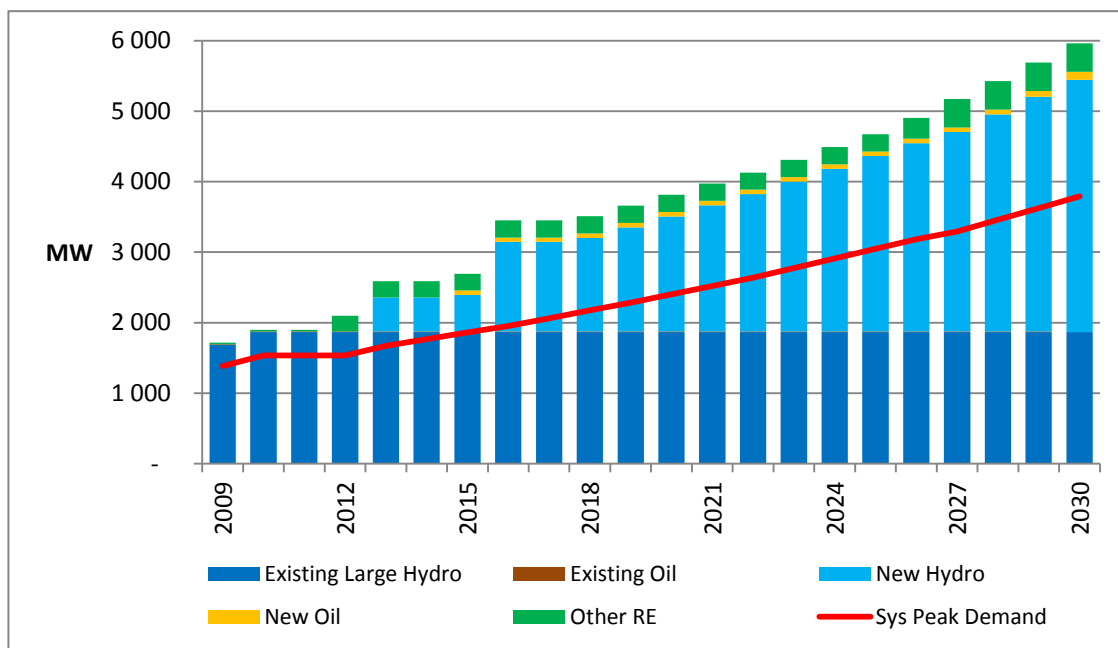


Figure 4.3 Least cost capacity mix to meet Base-Case demand

The red solid line shows the System Peak Demand (SPD). In 2009, the SPD was 1 384 MW and is expected to rise to 3 794 MW by 2030. It should be noted that SPD only accounted for electricity demand that was served – the projections were made based on the served electricity demand.

New installed capacity, shown in figure 4.4 below, is dominated by hydro plants as anticipated from the LCoE analysis. New oil plants come online to serve as peaking plants. About 200 MW of solar PV comes online to meet the growing demand in 2012 since it was the only supply option.

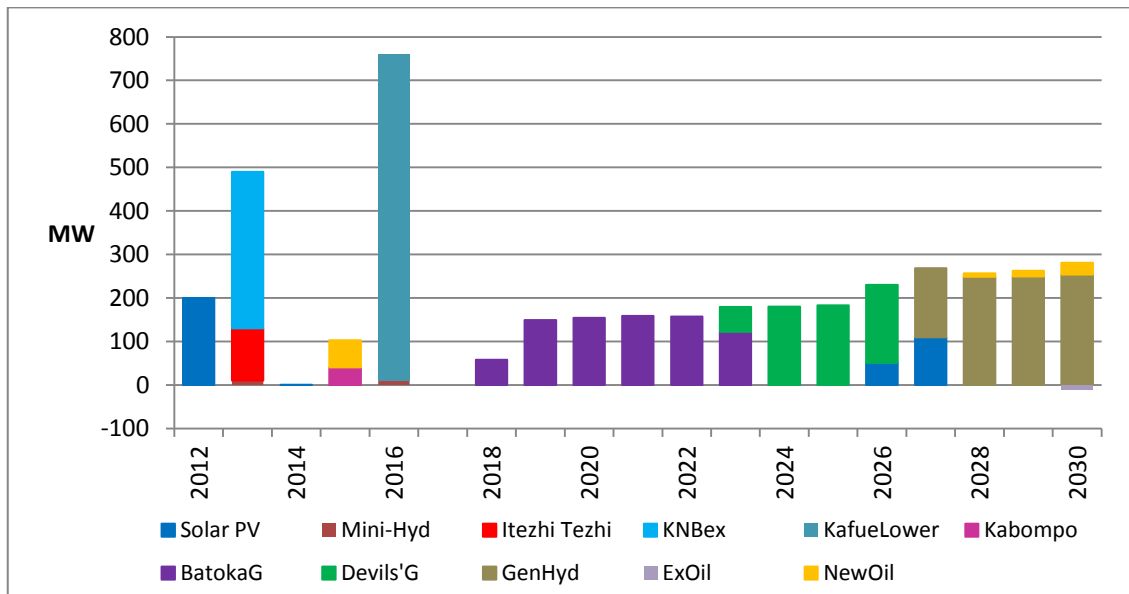


Figure 4.4 Annual additional capacity

The maximum electricity that can be generated from the total installed capacity (including 22.23 MW of imports) is shown in figure 4.5 below. The red line shows the total electricity demand at secondary level.

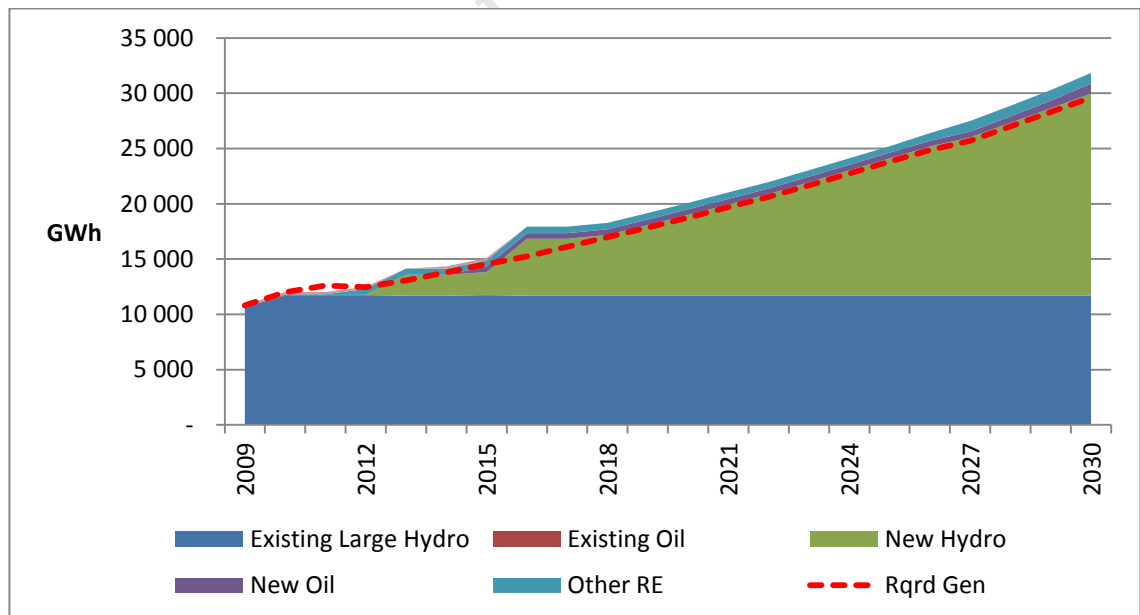


Figure 4.5 Maximum electricity generation based on the available capacity

The required capital costs to develop the capacity shown in figure 4.4 above is \$9 822 million. The investment expenditure plan is as shown in figure 4.6 below.

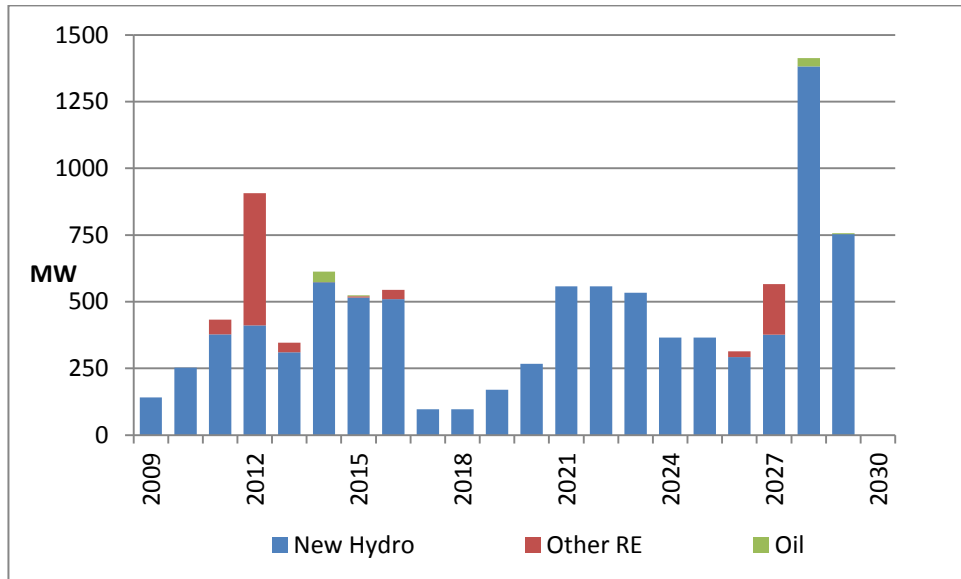


Figure 4.6 Investment Expenditure Plan

The stacked system costs for generating electricity are shown in figure 4.7 below. The figure shows that there is sharp increase in the generating cost from 2012 to 2016. The cost increases because of the capital investment into the system during this period. The generating cost then gradually increases to \$36.68/MWh (2030) from \$27.10/MWh (2016).

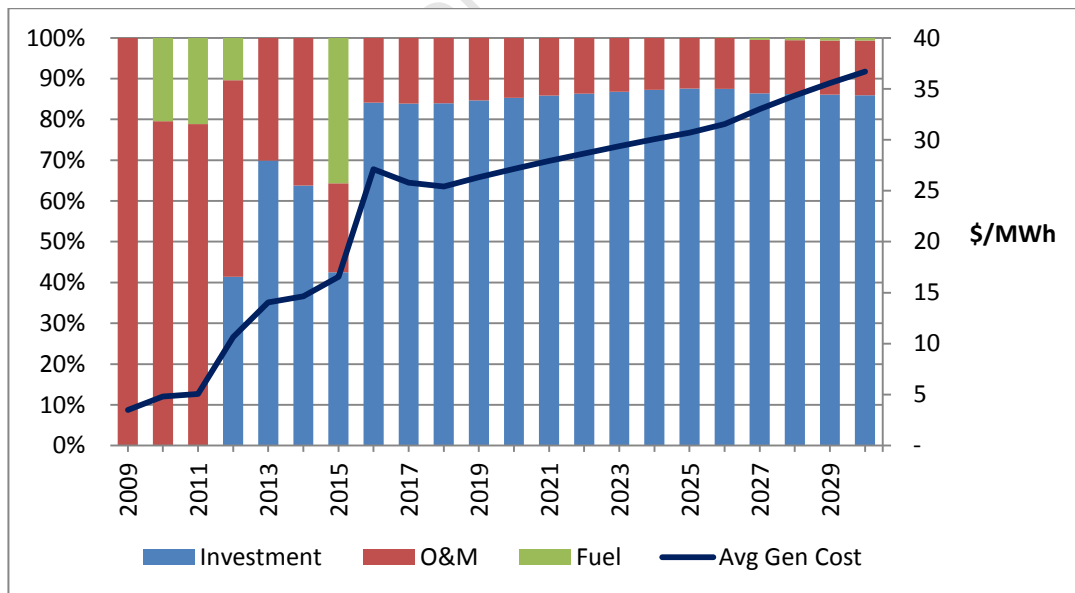


Figure 4.7 Shares of system costs and the average generating cost

The system losses shown in figure 4.8 below is dominated by the distribution losses to ‘Other’ demand sectors, and are significant, reaching 4 800 GWh in 2030. It would therefore, be

essential that transmission efficiency of ‘Other’ distribution network be improved to minimised losses. This would also help to reduce the system costs¹⁴.

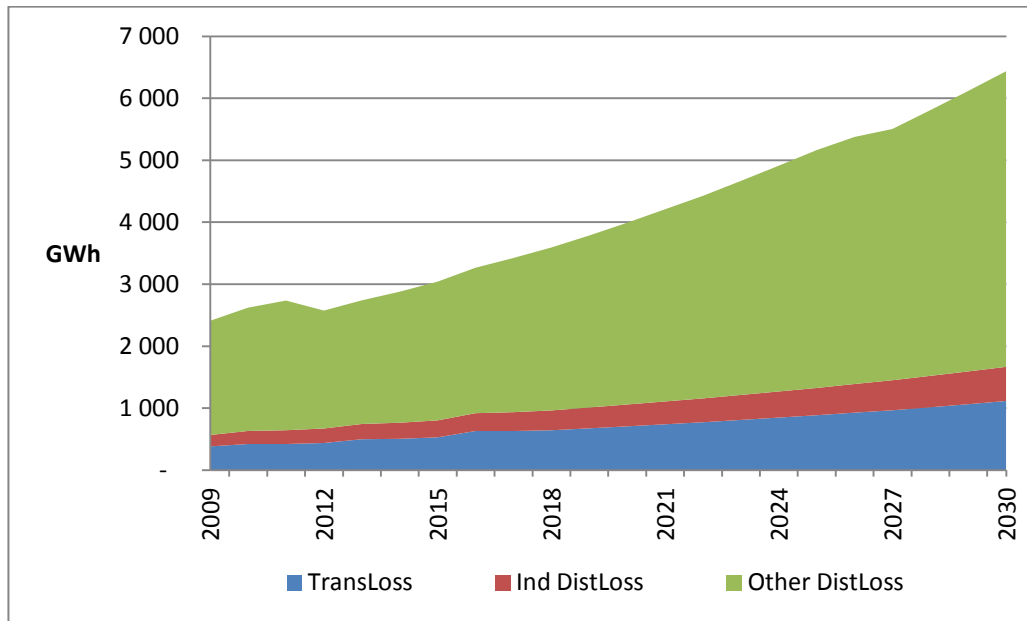


Figure 4.8 System losses

4.3.2.2. Comparison of the three growth scenario systems

In order to meet demand under the HG and LG scenarios (as shown in Table 4.1 above), the total capital investment cost of \$23 836 million and \$5 125 million respectively would be required.

Electricity generation capacity for both BC and LG¹⁵ systems continue to be dominated by hydro plants, while the HG system is more diverse (hydropower accounts for 56% in 2030). This can be seen in the SWI indicators shown in Table 4.3 below, where the HG system reaches 0.324 in 2030.

Table 4.3 The SWI for the three least cost systems

	2009	2015	2020	2025	2030
HG System	0.0173	0.2407	0.1678	0.2725	0.3235
BC System	0.0173	0.0846	0.0295	0.0235	0.0316
LG System	0.0173	0.0063	0.0070	0.0074	0.0404

The least cost system for the three demand scenarios leads to CO₂ emissions of 1 142, 6.2 and 1.1 kton for HG, BC and LG systems respectively throughout the analysis period.

¹⁴ Appendix D, Table D3 Annualised system costs

¹⁵ Appendix E, Figure E1 Total installed capacity for LG demand scenario

The average generating cost in all growth demand scenarios increase sharply from 2012 to 2016 as shown in figure 4.9 below. This is mainly because of the increased capital investment into the system and use of oil plants. However, in LG scenario, the spike in generating cost only happens in 2016 because of the delayed capacity development.

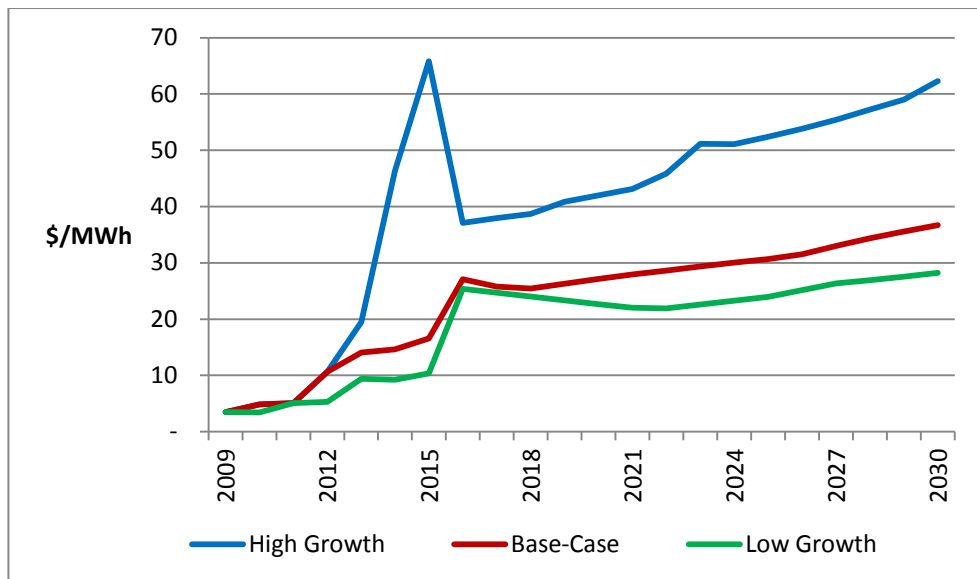


Figure 4.9 Average generating cost of the three growth scenarios

Figure 4.10 below shows the Reserve on Energy (RoE) share for the system developed with a reserve margin (RM) of 15% for all the three demand scenarios. It can be observed that HG system have a higher RoE than BC and LG systems. This is because ‘Other’ demand for HG system experienced a higher growth over Industrial demand, which led to the building of more capacity to meet peak demand.

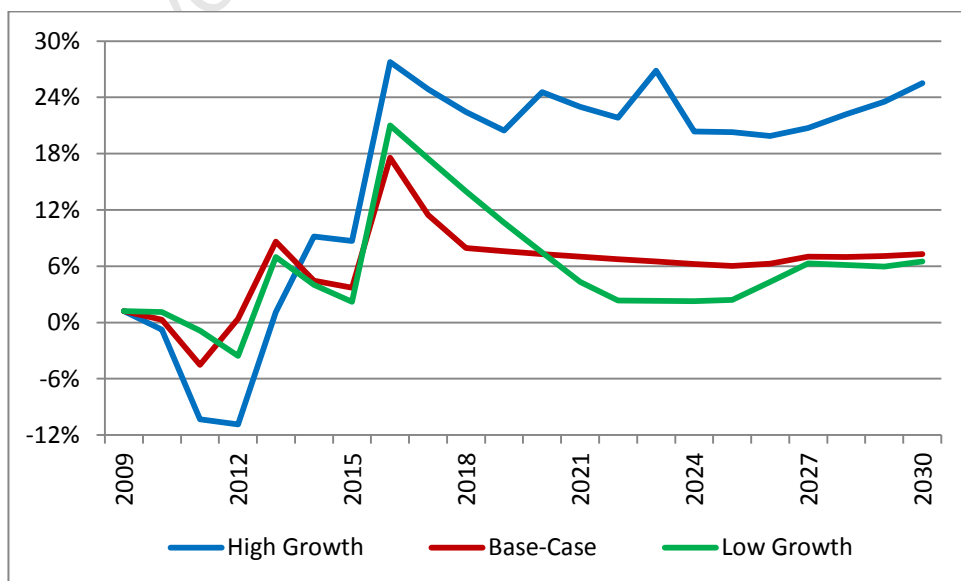


Figure 4.10 Reserve on Energy for all the three systems

4.3.3. Dry year scenario Results

This section focuses on developing an electricity supply plan that is required to achieve the middle income industrialised country target, assuming both average and dry year scenarios.

Figure 4.11 below shows the least cost installed capacity that would be required to meet the demand under average year scenario. With a constraint on electricity importation of 22.23 MW, oil and gas plants are predominately operated as peaking plants. Of the 6 615 MW non-large hydro capacity that is built by 2030, 3 498 MW is from RE technologies. Capacity of 200 MW of gas and 76 MW of solar CSP technologies are also built in 2020 and 2030 respectively. There is however, uncertainty associated with the development of both gas and solar CSP technologies in Zambia. Gas technology development would require significant investments in importation and handling infrastructure, while land area requirement and future uncertainty of capital investment cost would hinder the development of solar CSP (as earlier discussed in Section 2.7). Since gas plants are mainly operated during peak periods, electricity imports or oil plants could be used as alternative, while solar CSP can be replaced by solar PV.

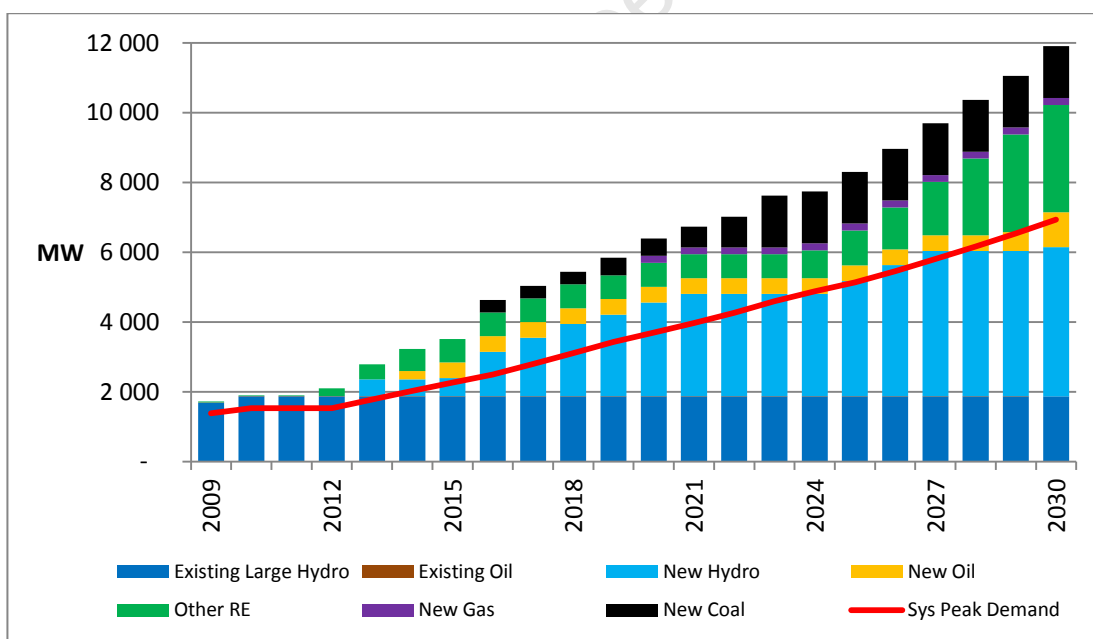


Figure 4.11 Least cost capacity mix to meet High Growth demand

The Generation Expansion Plan for the least cost system in an average year scenario is shown in Table 4.4 below.

Table 4.4 Electricity Generation Expansion Plan in an average year scenario

	Committed build	New build options							Total New build	System Peak (Sent Out)
	Hydro	Hydro	Coal	Solar PV	Solar TW	Bio	Gas	Oil		
	MW	MW	MW	MW	MW	MW	MW	MW		
2009	0	0	0	0	0	0	0	0	0	1384
2010	0	0	0	0	0	0	0	0	0	1533
2011	0	0	0	0	0	0	0	0	0	1533
2012	0	0	0	200	0	0	0	0	200	1533
2013	480	0	0	200	0	0	0	0	680	1776
2014	0	0	0	200	0	0	0	241	441	2028
2015	40	0	0	38	0	0	0	207	285	2265
2016	750	0	356	0	0	0	0	0	1106	2497
2017	0	400	0	0	0	0	0	0	400	2800
2018	0	400	6	0	0	0	0	0	406	3109
2019	0	264	138	0	0	0	0	0	402	3427
2020	0	353	0	0	0	0	200	0	553	3695
2021	0	247	88	0	0	0	0	0	336	3973
2022	0	0	286	0	0	0	0	0	286	4261
2023	0	0	607	0	0	0	0	0	607	4592
2024	0	0	0	116	0	0	0	0	116	4878
2025	0	364	0	200	0	0	0	0	564	5134
2026	0	461	0	200	0	0	0	0	661	5459
2027	0	402	0	200	0	130	0	0	732	5800
2028	0	0	0	200	0	470	0	0	670	6159
2029	0	0	0	200	0	400	0	91	691	6537
2030	0	120	0	200	76	0	0	460	857	6935

The evolution of the electricity system in the dry year scenario is as shown in figure 4.12 below. The system without a diversification policy (DryY_WithoutDiv) will require additional capacity of RE, gas and coal technologies while deliberate diversification (DryY_WithDiv) of the system could lead to delay in development of hydropower, gas and oil technologies in preference to development of coal and RE technologies.

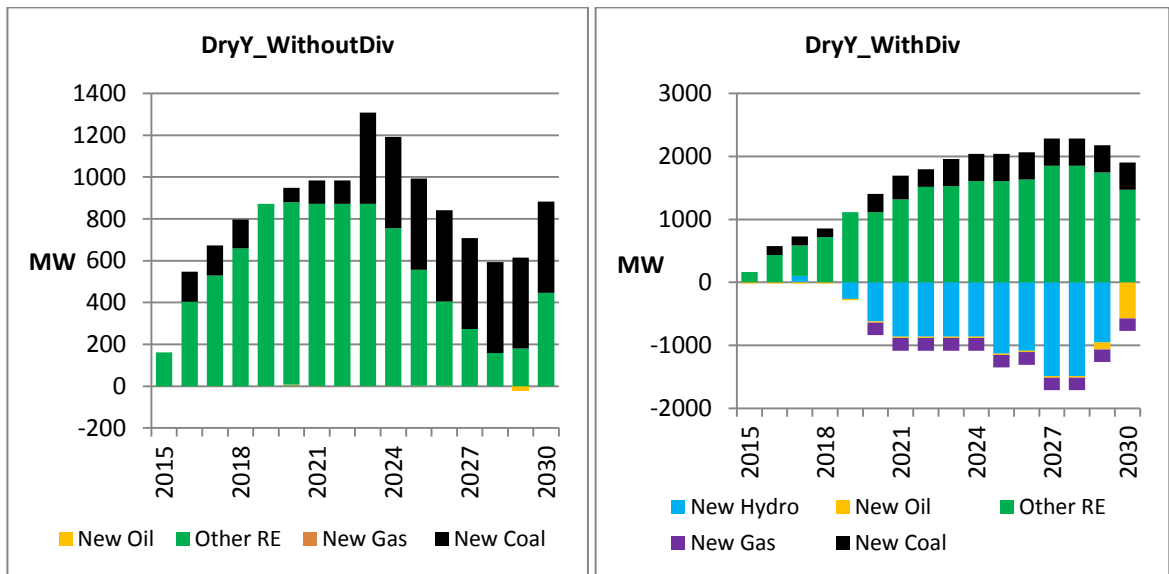


Figure 4.12 Annual additional required capacity under dry year scenario

The total installed capacity increase by 1 128 and 883 MW for systems with and without a diversification policy respectively in a dry year scenario. The additional capacity shown in figure 4.12 is what needs to be built in order to improve the adaptive capacity of systems (both with and without a diversification policy).

The diversification policy would require \$3 738 million of additional capital investment compared to the least cost system in an average year scenario, while the system without a diversification policy would only require \$2 612 million. Although there are higher costs (capital investment and fixed Operation and Maintenance) in a system with a diversification policy, there is a small difference in the average generating cost between a system with and without a diversification policy as shown in figure 4.13 below.

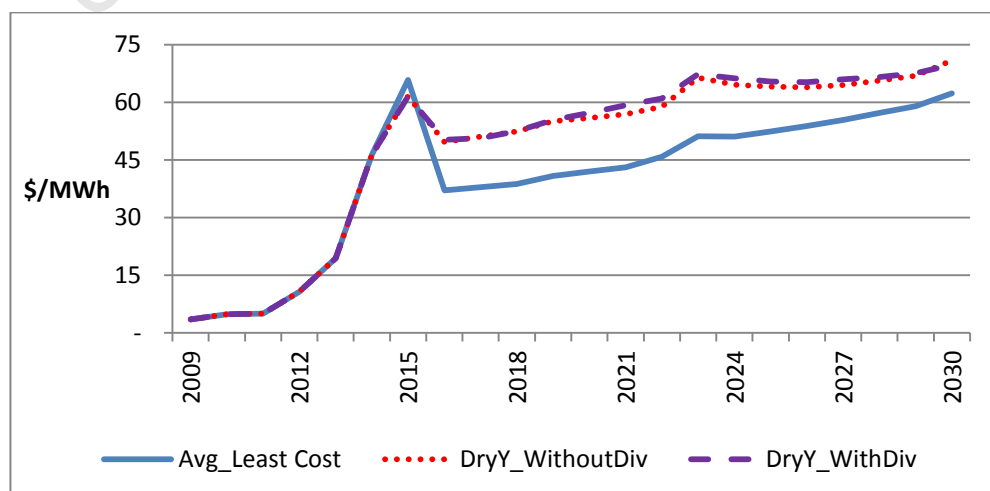


Figure 4.13 Average generating cost for all the three scenarios

There are lower CO₂ emissions in the system without a diversification policy; the difference however, is minimal. Least cost options leads to 1 416 kton CO₂ emissions while diversification policy leads to 1 473 kton throughout the analysis period.

It should be noted that the diversification policy requires a more aggressive approach to investment in RE technologies. Therefore, if Zambia opts to diversify the electricity system, additional policies and institutional frameworks that are required for the development of RE technologies have to be in place.

With SAPP planning to develop a regional grid among its member states, trade policy would be critical in the electricity planning phase. Some of the effects of dry year could possibly be easily mitigated by importing electricity provided the exporting countries are not affected in the same way as Zambia. Also, the grid could be used to export excess electricity.

As seen in figure 4.13 above, the system generating cost increases sharply in 2014 and 2015 due to the increased capital investment and operation of oil power plants. Importing electricity during this period would delay the need to build capacity and operating of RE and oil technologies, since the cost of importing electricity would be cheaper as shown in figure 4.14 below. However, this option is only feasible as long as electricity is available on the market.

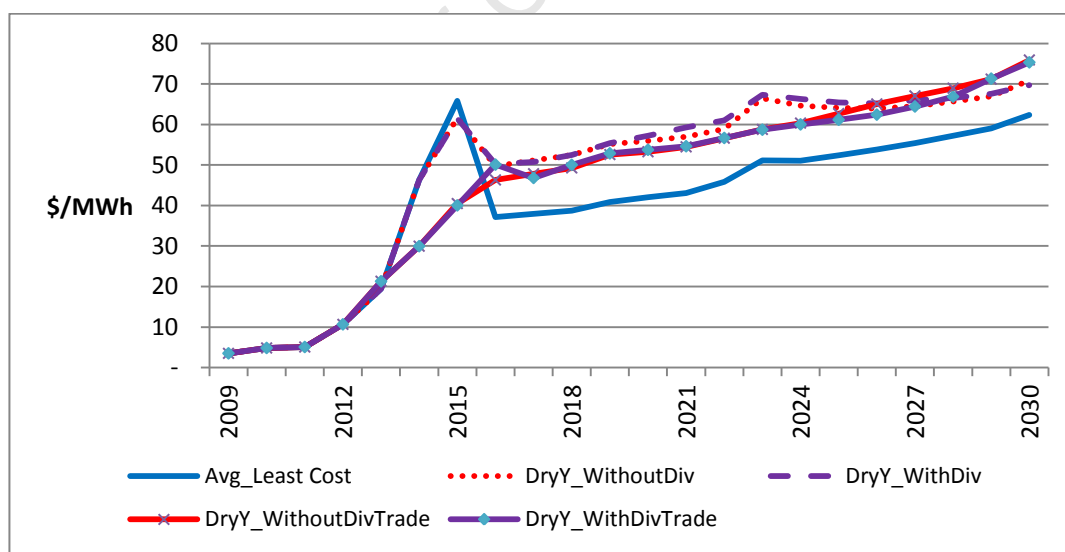


Figure 4.14 Average generating cost for all three scenario including trade policy

Electricity imports could possibly reduce the average generating costs, and it could also reduce the need for capital investment. Trade policy¹⁶ would also delay the need for oil, gas and some coal plants. Nonetheless, increase in imports may in the long run lead to energy insecurity.

¹⁶ Appendix E, Table E2 Total Installed capacity with a trade policy for HG demand scenario

Since there is uncertainty of how the electricity demand would evolve, there could as well be excess in electricity in an event that Zambia’s economy follows the BC or LG scenario. Such an event would put Zambia in a position of being a net exporter of electricity, albeit not desirable turn of events. But because capacity development decisions are made based on the feedback from the economy, some generation projects can be delayed in order to avoid this excess.

4.3.3.1. Sensitivity Tests results for the system without a diversification policy

Sensitivity tests were carried out on the system, with and without a diversification policy, in a dry year scenario. Parameters chosen for the sensitivity analysis were the discount rates (6% & 14%), carbon price (\$ 25 & \$ 50 per tonne) and pessimistic learning for RE technologies. Overall, the system without a diversification policy was still cost effective.

Discount Rates

There is early development of additional capacity in solar PV at the discount rate of 6%, while investment in solar CSP and bio technologies is delayed as shown in figure 4.15 below. By 2030, the installed capacity is 12 762 MW (22 MW less than that of the system at 10% discount rate). At 6% discount rate, electricity generation from solar PV is favoured over coal, gas, oil and bio technologies. At a discount rate of 14% however, there is more capacity development in bio and oil technologies while there is delay in the development of solar PV, generic coal and solar CSP technologies as shown in figure 4.15 below. By 2030, the installed capacity is 12 559 MW. Electricity supply from imports, gas, oil, and bio technologies increases. Generally, both discount rates lead to minimal increase in the average generating cost, with discount rate of 14% leading to smaller increase. This increase is mainly attributed to the increase of solar PV in the systems.

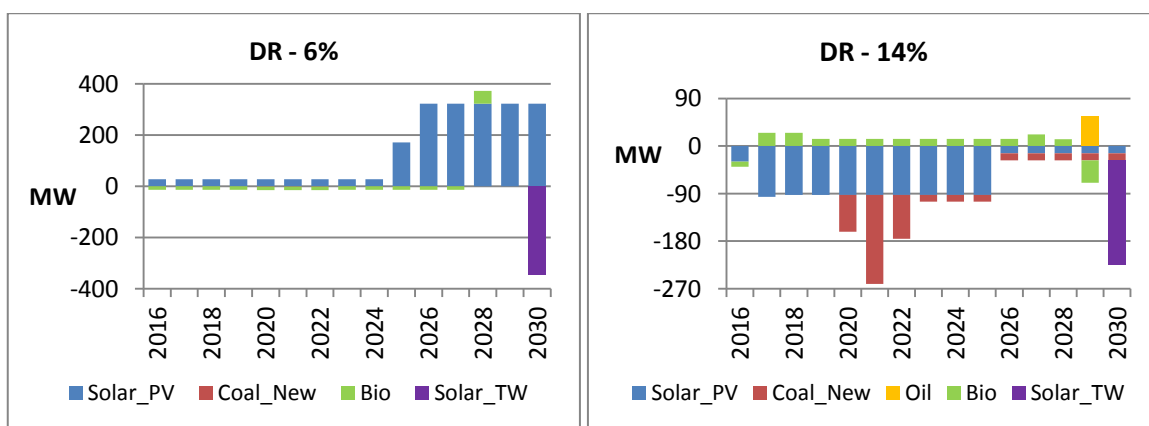


Figure 4.15 Effects of discount rates on capacity development

Carbon price

Both carbon price of \$25 and \$50 per tonne of carbon emission leads negligible change in the generating cost and capacity mix.

Pessimistic RE costs

A pessimistic learning rate leads to a minimal reduction in the average generating cost. It also leads to delay in capacity development of solar PV technology while favouring development of solar CSP and bio technologies as show in figure 4.16 below. The installed capacity in 2030 is 12 511 MW.

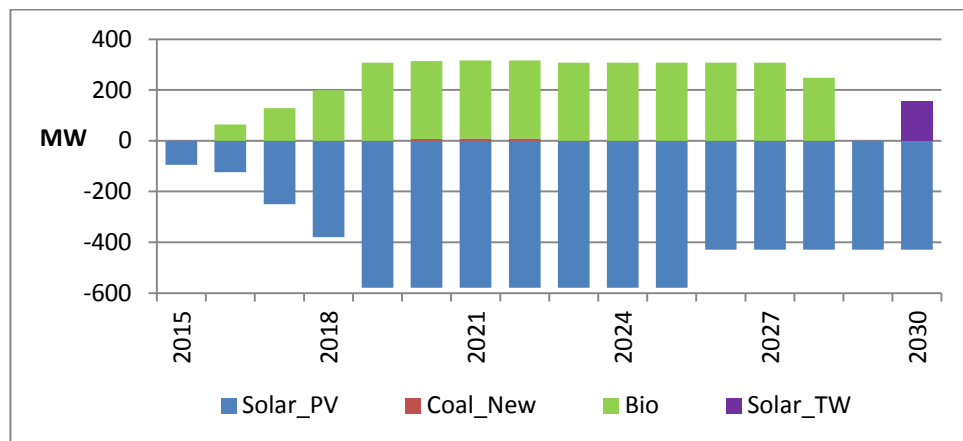


Figure 4.16 Effects of pessimistic learning rate on capacity development

4.3.4. Proposed Plan

As shown above, the system without a diversification policy still requires additional capacity in order to minimise the impacts of dry year on the generating cost. Further, trade policy could offer a cheaper option of mitigating the impacts of dry year. Nonetheless, availability of electricity on the regional market is not guaranteed as the SAPP region is experiencing electricity shortage and it is not known when sufficient electricity will be available. The other concern with the trade policy could be price uncertainty. Combining these options (additional capacity and trade policy) would reduce both the risks of a dry year and energy security concerns, but raises the generating cost in an average year as shown in figure 4.17 below.

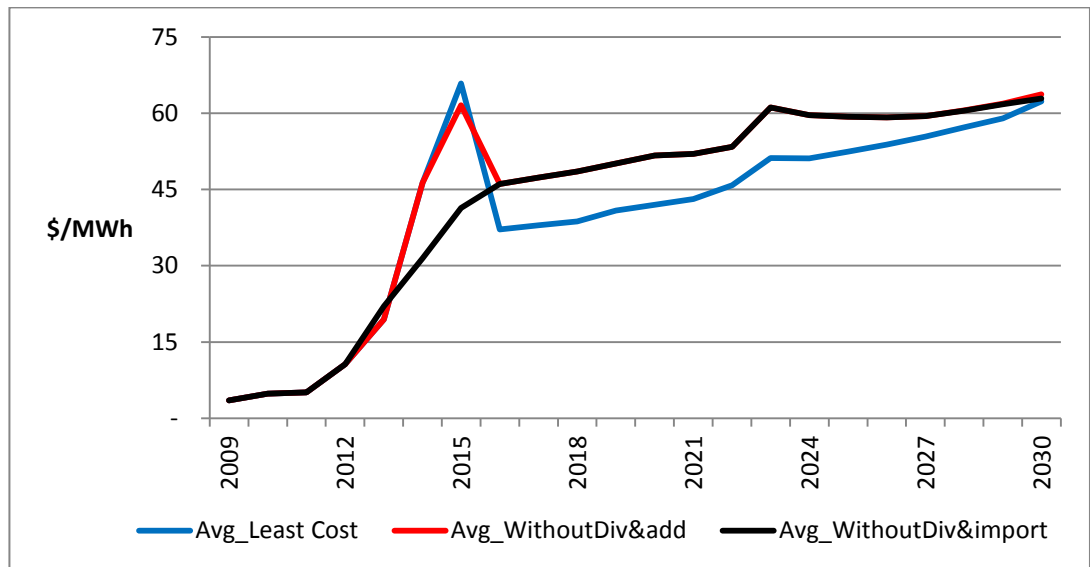


Figure 4.17 Average generating cost for the proposed plan

The figure above shows that trade policy could play a critical role in reducing the generating cost in 2014 and 2015. After 2015, imports would continue playing a significant role as there is still uncertainty over the development of gas and solar CSP technologies in Zambia. The proposed plan as shown in Table 4.5 below includes all needed additional capacity (as identified in figure 4.12) and trade policy.

Table 4.5 Proposed Electricity Generation Expansion Plan

	Committed build	New build options							Total New build	System Peak (Sent Out)
	Hydro	Hydro	Coal	Solar PV	Solar TW	Bio	Gas	Oil		
	MW	MW	MW	MW	MW	MW	MW	MW		
2009	0	0	0	0	0	0	0	0	0	1384
2010	0	0	0	0	0	0	0	0	0	1533
2011	0	0	0	0	0	0	0	0	0	1533
2012	0	0	0	200	0	0	0	0	200	1533
2013	480	0	0	200	0	0	0	0	680	1886
2014	0	0	0	200	0	0	0	242	442	2028
2015	40	0	0	200	0	0	0	207	447	2183
2016	750	0	500	30	0	212	0	0	1492	2400
2017	0	400	0	124	0	0	0	0	524	2639
2018	0	400	0	130	0	0	0	0	530	2882
2019	0	265	0	200	0	11	0	0	476	3103
2020	0	360	70	0	0	0	200	0	630	3367
2021	0	240	131	0	0	0	0	0	371	3644
2022	0	0	287	0	0	0	0	0	287	3933
2023	0	0	930	0	0	0	0	0	930	4264
2024	0	0	0	0	0	0	0	0	0	4608
2025	0	365	0	0	0	0	0	0	365	4966
2026	0	460	0	49	0	0	0	0	509	5368
2027	0	400	0	200	0	0	0	0	600	5709
2028	0	0	0	200	0	355	0	0	555	6068
2029	0	0	0	200	0	421	0	70	691	6447
2030	0	120	0	200	344	0	0	481	1145	6844

5. Conclusion & Recommendation

The first section of this chapter presents a brief summary of key points and conclusions. The second section gives recommendations that should be considered in order to improve the outputs of this research.

5.1. Summary and Conclusion

The baseline for electricity consumption in Zambia was established. The demand model was then developed using LEAP software and electricity demand was projected up to 2030. The mining & quarry sub-sector continues to dominate electricity demand in all the three growth paths. Residential sector demand is influenced heavily by increase in number of HH connections.

MESSAGE platform was used to model the supply system. The output of the model was further analysed using Excel spreadsheet. Different demand and climatic scenarios were explored.

In an average year, the results show that Zambia's electricity generation capacity has to be increased from 1 719 MW (in 2009) to 4 193 MW (for Low Growth), 5 983 MW (for Base-Case), and 11 901 MW (for High Growth) by 2030. Hydropower continues to dominate in all the three systems. Low and Base-Case Growth scenarios would require deliberate policy in order for the system to be diversified and made climate resilient, while under the High Growth scenario, the least cost option leads to a diversified system (hydro accounts for 56% by 2030).

With technology learning, RE technologies plays a major role in future electricity supply in Base-Case and High Growth scenarios. The pessimistic technology learning rate delays the development of solar PV but favours bio technology. Importation of electricity however, leads to delay in development of RE technologies.

Large hydropower option continues to remain competitive even in dry year scenario. Therefore, Zambia should continue developing hydropower, as this could also help off-set CO₂ emissions in the SADC region. With increasing fuel costs, electricity generation from oil and gas plants is limited to peak periods.

The impact of a dry year on the average generating cost is significant. With limited importation capacity of 22.23 MW in a system designed for high demand, the generating cost for the system without a diversification policy increases by an average of 18.2% while for a system with a diversification policy, the generating cost increases by 19.5% relative to the

least cost system in average year scenario. However, if importation capacity limit is increased from the current 22.23 MW to 2 060 MW, the generating cost in a dry year scenario only increases by an average of 12.1% and 11.8% for the system without and with a diversification policy respectively. Therefore, trade policy could be used as a measure to keep the generating cost low during dry years.

The total capital investment required to develop a high demand system with a diversification policy (with limited importation) would be about 15.7% more than average year least cost system, while only 11% increase would be required for a system without a diversification policy. Therefore, least cost system with deliberate inclusion of non-large hydro technology as identified in figure 4.11 would be the most cost effective strategy of developing an adaptive system.

In a system without a diversification policy, a carbon price of \$25 per tonne (by 2030) has no effect on the build on CO₂ emitting technologies while the \$50 per tonne has a minimal effect. There is a minimal reduction of 4 MW in coal technology which is replaced by RE technologies. Therefore, if the carbon price is \$50 per tonne or less, the coal would be a viable option for base-load provision.

Trade policy would play a critical role in Zambia's future energy policy. Currently, Zambia is a net exporter but with increase in demand and long lead time for technologies to come online, Zambia should consider becoming a net importer of electricity, at least in the interim. This would help to keep the average generating cost low and avoid developing expensive supply technologies.

Therefore, the best electricity expansion path for Zambia (i.e. under high demand) is the least cost path with additional capacity and trade policy as discussed in Section 4.3.4.

5.2.Recommendations

In order to improve the demand projections, demand should be built up from end-use level. This could also help identify areas which offer energy efficiency or fuel switching opportunities. Further, including the rural-urban split in modelling of the residential sector would also help in deciding how best electricity can be supplied – using grid or off-grid systems.

Physical output (kWh/tonne) and floor space (kWh/m²), not value addition (kWh/\$), should be used when modelling the economic sectors so that the effects of fluctuating commodity prices on electricity intensity could be avoided.

Better information on the potential of solar (both PV and CSP) and bio technologies should be included in the supply model, so that the better assessment of these technologies' participation can be made.

Using an optimisation model, such as TIMES, with a price elasticity function could also help understand how demand would change under different supply scenarios.

Detailed transmission and distribution network analysis should be done in order to assess the impact that off-grid technologies would have on the electricity system.

Analysing the supply system on a platform, such as TIMES, which can account for the probability of a dry year occurring would improve the picture of the proposed electricity expansion plan. MESSAGE was used in this case because the primary focus of the study was to compare the performance of two systems (with and without a diversification policy) in a dry year scenario (2016 to 2030).

Developing a regional model that enables trade between countries would give a better and clearer picture of how Zambia's electricity system could best be developed.

Both Demand and Supply Side models should be constantly updated with new and better information for them to be of use to decision and policy makers in Zambia.

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Appendices

University of Cape Town

Appendix A

Table A1. Techno-economic data of existing plants

Station Name	Main Output	Main Output	var costs US\$'00/kWyr	Avg Availability	Dry Year Availability	Plant life Yr	Total Capital Cost US\$'00/kW	Fixed Costs US\$'00/kW/yr	Hist. cap. (switch hc)
	Name			Share	Share				MW (year)
Existing Oil	Elec/Sec	0.30	27.6	0.85	0.85	30	0	8.40	10 (2000)
Kariba North Bank	Elec/Sec	1.00	13.9	0.65	0.51	50	0	9.16	540 (2000), fx 180 (2010)
Kafue Gorge	Elec/Sec	1.00	13.9	0.77	0.64	50	0	9.16	660 (2000), fx 130 (2009)
Vic Falls	Elec/Sec	1.00	13.9	0.71	0.47	50	0	9.16	108 (2000)
Small hydro	Elec/Sec	1.00	13.9	0.61	0.40	50	0	9.16	46.5 (2000)
Mini hydro	Elec/Fin	1.00	13.9	0.29	0.29	30	0	9.16	24 (1995)

Sources:

1. SAPP Regional Generation and Transmission Expansion Plan Study: Main Report (Nexant 2007)

Table A2. Techno-economic data of potential projects (2008 prices)

Project Name	Main Output	Main Output	var costs US\$'00/kWyr	Avg Availability	Dry Year Availability	Plant life Yr	Total Capital Cost* US\$'00/kW	Fixed Costs US\$'00/kW/yr	bdc (up)	bdc (fx)
	Name			Share	Share				MW	MW (year)
Maamba Coal	Elec/Sec	0.37	8.8	0.93	0.93	35	2898.4	20.98	500	
Itezhi Tezhi	Elec/Sec	1.00	13.9	0.66	0.43	50	3012.4	9.16	120	(120) 2013
Kariba North Extension	Elec/Sec	1.00	13.9	0.38	0.30	50	1054.0	9.16	360	(360) 2013
Kafue Gorge Lower	Elec/Sec	1.00	13.9	0.47	0.36	50	2752.8	9.16	750	750 (2016)
Kalungwishi	Elec/Sec	1.00	13.9	0.49	0.32	50	3754.6	9.16	210	
Kabompo	Elec/Sec	1.00	13.9	0.48	0.32	50	4716.8	9.16	40	40 (2015)
Batoka Gorge	Elec/Sec	1.00	13.9	0.68	0.54	50	2420.2	9.16	800	
Devils Gorge	Elec/Sec	1.00	13.9	0.68	0.54	50	2439.2	9.16	600	
New Gas	Elec/Sec	0.48	24.9	0.95	0.95	30	1307.2	21.01	1000	
New Oil	Elec/Sec	0.30	8.8	0.93	0.93	30	708.8	8.40	1000	
New Coal	Elec/Sec	0.37	54.1	0.91	0.91	30	3423.2	25.72	4000	
New Bio	Elec/Sec	0.38	36.8	0.89	0.89	30	4029.5	136.58	1000	
New Solar CSP	Elec/Sec	1.00	0.0	0.43	0.43	30	6243.7	86.15	500	
New Solar PV	Elec/Fin	1.00	0.0	0.27	0.27	25	3333.0	71.44	3000	
New mini hydro	Elec/Fin	1.00	0.0	0.30	0.30	25	4166.3	71.44	30	10 (2010), 10 (2013), 10 (2016)
New Hydro	Elec/Sec	1.00	0.00	0.60	0.40	50	2758.4	47.76	1490	

* New hydro (bdi (up)) is 2016 (90MW), 2018 (270MW), 2020 (450MW) and 2022 (1490MW)

*This includes the cost transmission lines into the grid (based on simple calculations – See Table A6)

Source:

1. SAPP Regional Generation and Transmission Expansion Plan Study: Main Report (Nexant 2007)
2. Proposed Kabompo Gorge Hydro Electric Scheme: Environmental Impact Statement (DHEC 2011)

Table A3. Total Capital Investment Costs for RE technologies with technology learning

Costs for Optimistic Learning Rate	2010	2013	2016	2019	2022	2025	2030
New mini hydro	4096	3990	3884	3778	3727	3704	3666
New Bio	3961	3859	3756	3654	3605	3583	3545
New Solar PV	3019	2602	2243	1934	1667	1437	1122
New Solar CSP	5460	4464	3650	2985	2441	1996	1427
Costs for Pessimistic Learning Rate	2010	2013	2016	2019	2022	2025	2030
New mini hydro	4137	4092	4048	4004	3982	3972	3955
New Bio	4001	3958	3915	3872	3851	3842	3825
New Solar PV	3206	3023	2852	2689	2537	2392	2170
New Solar CSP	5924	5474	5059	4675	4320	3993	3501

Sources:

1. Integrated Resource Plan for Electricity 2010-2030 (RSA 2011)
2. Energy Technology Perspective: Scenarios & Strategies to 2050 (IEA 2008)

Table A4. Fossil fuel price projections

Current Scenario	2009	2015	2020	2025	2030
Fuel Oil (\$/kWyr)	382.85	595.72	697.26	760.65	824.04
Coal (\$/kWyr)	63.92	64.25	69.51	71.94	73.91
Gas (\$/kWyr)	280.99	370.55	415.33	445.29	475.25
New Policy Scenario	2010	2013	2016	2019	2030
Fuel Oil (\$/kWyr)	382.85	573.01	627.57	665.72	697.58
Coal (\$/kWyr)	63.92	64.19	66.82	68.39	69.38
Gas (\$/kWyr)	280.99	364.56	400.51	424.47	445.29

Sources:

1. World Energy Outlook 2010 (IEA 2010)
2. SAPP Regional Generation and Transmission Expansion Plan Study: Main Report (Nexant 2007)
3. Integrated Resource Plan for Electricity 2010-2030 (RSA 2011)

Table A5. Electricity import price projections

	2009	2010	2013	2016	2019	2022	2025	2030
Import price (S/kWyr)	350	419	680	964	1099	1148	1148	1148

Sources:

1. Integrated Resource Plan for Electricity 2010-2030 (RSA 2011)
2. <http://www.sapp.co.zw/viewinfo.cfm?linkid=13&siteid=1> (SAPP 2012)

Table A6. Simple calculation for transmission lines that connect the plant to the grid

Name of Plant	Type of line to be constructed	US\$/Km	Approx Distance to Grid - Km	Total Cost - in US\$	Cost/kW - in US\$/kW	Name of nearest Grid point
Maamba Coal fired	330kV	193 959	65	12607313	25.21	Muzuma
Itezhi-Tezhi	330kV	193 959	200	38791731	323.26	Muzuma
Kafue Gorge Lower	330kV	193 959	8	1551669	2.07	Kafue Gorge Upper
Kalungwishi	330kV	193 959	600	116375194	554.17	<i>Not sure</i>
Kabompo	132kV	129 306	100	12930612	323.27	<i>Not sure</i>
Batoka gorge	330kV	193 959	55	10667726	13.33	Vic Falls
Devil's gorge	330kV	193 959	100	19395866	32.33	Batoka Gorge
New Coal	330kV	193 959	65	12607313	3.15	Muzuma
New Hydro	132kV	129 306	110	14223673	9.55	<i>Various</i>

Sources:

1. SAPP Regional Generation and Transmission Expansion Plan Study: Main Report (Nexant 2007)

Table A7. CO₂ Emission factors

	ktons per MWyr
Processing Coal	3.04
Processing Gas	1.77
Processing Oil	2.34
Coal Plants	8.20
Gas Plants	3.67
Oil Plants	7.74

Source:

1. <http://www.iea.org/co2highlights/>

Table A8. Average monthly Load profiles for 'Other' demand

Hour of Day	January	February	March	April	May	June	July	August	September	October	November	December
1	3.09%	2.93%	2.95%	2.98%	3.07%	3.09%	3.04%	3.04%	3.20%	3.10%	3.44%	3.27%
2	2.99%	2.76%	2.88%	2.85%	2.98%	2.98%	3.00%	2.96%	3.12%	3.02%	3.36%	3.16%
3	2.91%	2.70%	2.87%	2.78%	2.96%	2.96%	2.91%	2.93%	3.03%	2.99%	3.27%	3.09%
4	2.93%	2.73%	2.75%	2.88%	2.94%	3.00%	2.94%	2.90%	3.04%	3.02%	3.28%	3.09%
5	2.99%	2.95%	2.91%	3.12%	3.20%	3.32%	3.24%	3.14%	3.19%	3.21%	3.47%	3.06%
6	3.49%	3.46%	3.32%	3.55%	3.81%	3.89%	3.80%	3.71%	3.88%	3.88%	4.03%	3.53%
7	4.14%	4.20%	4.15%	4.30%	4.49%	4.53%	4.40%	4.37%	4.42%	4.39%	4.18%	4.00%
8	4.48%	4.67%	4.83%	4.65%	4.68%	4.61%	4.65%	4.67%	4.71%	4.65%	4.33%	4.28%
9	4.57%	4.76%	5.02%	4.91%	4.69%	4.74%	4.72%	4.86%	4.77%	4.69%	4.33%	4.45%
10	4.61%	4.78%	4.94%	4.59%	4.51%	4.55%	4.59%	4.69%	4.60%	4.50%	4.20%	4.52%
11	4.54%	4.65%	4.71%	4.46%	4.44%	4.48%	4.44%	4.53%	4.46%	4.38%	4.22%	4.47%
12	4.54%	4.72%	4.63%	4.72%	4.57%	4.59%	4.50%	4.56%	4.57%	4.54%	4.47%	4.47%
13	4.73%	4.79%	4.89%	5.06%	4.80%	4.77%	4.71%	4.69%	4.67%	4.59%	4.49%	4.63%
14	4.60%	4.57%	4.78%	4.57%	4.45%	4.38%	4.46%	4.32%	4.26%	4.19%	4.26%	4.57%
15	4.17%	4.40%	4.39%	4.05%	4.04%	3.97%	4.11%	4.07%	3.97%	3.90%	4.01%	4.38%
16	3.89%	4.18%	4.12%	3.97%	3.94%	3.88%	4.04%	3.99%	3.88%	3.75%	4.03%	4.09%
17	3.87%	4.15%	4.07%	4.08%	4.12%	3.94%	4.08%	4.05%	3.81%	3.78%	4.04%	4.10%
18	4.15%	4.37%	4.30%	4.51%	4.84%	4.63%	4.67%	4.68%	4.57%	4.32%	4.26%	4.17%
19	4.81%	5.01%	5.02%	5.77%	5.65%	5.59%	5.46%	5.41%	5.58%	5.61%	5.16%	4.70%
20	5.67%	5.39%	5.11%	5.78%	5.33%	5.49%	5.47%	5.39%	5.29%	5.74%	5.41%	5.24%
21	5.62%	5.30%	5.00%	5.18%	4.94%	5.11%	5.15%	5.07%	4.98%	5.36%	5.17%	5.32%
22	5.15%	4.85%	4.77%	4.58%	4.35%	4.41%	4.57%	4.52%	4.62%	4.74%	4.73%	5.07%
23	4.44%	4.18%	4.10%	3.69%	3.80%	3.74%	3.75%	3.92%	3.93%	4.13%	4.15%	4.51%
24	3.62%	3.51%	3.47%	3.00%	3.41%	3.37%	3.30%	3.50%	3.46%	3.52%	3.72%	3.85%

Note: Other demand consists of agricultural, services and residential demands

Sources:

1. Based on ZESCO Limited statistics (Personal Communication 2012)

Table A9. Simple calculations for transmission and distribution network costs (based on IPA (2007) & Roussouw (2010))

Network Name	Cost (\$/Kwyr)
Transmission	40.66
Industrial Distribution & Supply	40.66
Other Distribution & Supply	243.94

Appendix B

Table B1. Final electricity consumption

Sector/Year	2005	2006	2007	2008	2009
Total (GWh)	8003.0	8528.0	8067.0	7357.0	7820.9
Agricultural (GWh)	94.0	89.0	188.0	166.0	176.0
Services (GWh)	802.0	760.0	651.0	674.0	716.1
Industrial (GWh)	5572.0	6020.0	5245.0	4495.0	4778.8
Mining&Quarry (GWh)	3982.3	4410.0	4735.8	4005.4	4258.8
Other Ind (GWh)	465.9	1610.0	509.2	489.6	520.0
Residential (GWh)	1535.0	1659.0	1983.0	2022.0	2150.0

Sources:

1. ERB Energy Sector Reports 2005, 2006, 2007 and 2008)
2. <http://data.un.org/Data.aspx?d=EDATA&f=cmID%3aEL>

Table B2. GDP contribution per sector (in \$' million constant 2005 ppp)

	2005	2006	2007	2008	2009	2010
Agricultural (\$' million)	1955.5	2050.4	2025.8	2043.3	2193.5	2343.0
Services (\$' million)	7416.1	8133.7	8495.0	8974.2	9346.3	9988.5
Industrial (\$' million)	3897.1	3910.7	4446.9	4800.5	5291.2	5780.3
Mining&Quarry (\$' million)	1181.3	1300.4	1233.7	1336.4	1609.3	1857.4
Other Ind (\$' million)	2715.9	2610.2	3213.1	3464.2	3681.9	3922.9
Overall GDP (\$' million)	13268.8	14094.8	14967.7	15818.1	16831.0	18111.8

Sources:

1. MFNP Economic Report (2007)
2. BoZ Annual Reports (2009 and 2010)
3. <http://databank.worldbank.org/ddp/home.do?Step=1&id=4>

Appendix C

Table C1 Population and Household projections

	2013	2016	2019	2022	2025	2030
Population (x1000)	14 778.7	16 468.9	18 159.0	19 849.2	21 539.4	24 356.3
Households (x1000)	2 842.1	3 167.1	3 492.1	3 817.2	4 142.2	4 683.9

Table C2 Economic Projections for each growth scenario per sector

Low Growth Scenario	2013	2016	2019	2022	2025	2030
Agricultural (\$' million)	2836.5	3428.4	4137.1	5015.2	6066.5	8288.9
Services (\$' million)	10995.0	12083.5	13257.9	14613.4	16072.4	18740.1
Industrial (\$' million)	6249.5	6752.1	7289.6	7739.6	8204.8	9009.7
Mining&Quarry (\$' million)	1919.8	1981.2	2041.1	2079.6	2114.2	2162.3
Other Ind (\$' million)	4329.6	4770.9	5248.5	5660.0	6090.5	6847.4
Overall GDP (\$' million)	20080.9	22264.1	24684.6	27368.2	30343.6	36038.7
Base-Case Growth Scenario	2013	2016	2019	2022	2025	2030
Agricultural (\$' million)	2826.0	3408.4	4110.9	4959.5	5982.1	8172.8
Services (\$' million)	12033.9	14497.7	17465.5	21046.6	25357.3	34577.2
Industrial (\$' million)	6969.1	8402.8	10131.8	12209.5	14719.3	20117.7
Mining&Quarry (\$' million)	2212.9	2636.4	3140.8	3647.8	4235.9	5431.8
Other Ind (\$' million)	4756.2	5766.4	6990.9	8561.7	10483.5	14685.9
Overall GDP (\$' million)	21828.9	26308.9	31708.2	38215.7	46058.7	62867.7
High Growth Scenario	2013	2016	2019	2022	2025	2030
Agricultural (\$' million)	2936.0	3676.7	4601.2	5789.7	7258.8	10497.9
Services (\$' million)	12859.5	16544.6	21271.0	27498.2	35419.5	53583.0
Industrial (\$' million)	7750.3	10388.9	13921.9	18445.3	24576.3	40064.9
Mining&Quarry (\$' million)	2563.5	3535.5	4872.7	5607.5	6429.8	8013.0
Other Ind (\$' million)	5186.8	6853.4	9049.2	12837.8	18146.5	32051.9
Overall GDP (\$' million)	23545.8	30610.2	39794.0	51733.3	67254.6	104145.7

Appendix D

Table D1. S-Curves

Project Name	Expenditure Schedule (% per year)							
	8	7	6	5	4	3	2	1
Maamba Coal	0%	0%	0%	0%	10%	25%	45%	20%
Itezhi Tezhi	0%	0%	0%	0%	0%	15%	55%	30%
Kariba North Extension	0%	0%	0%	0%	10%	25%	20%	45%
Kafue Gorge Lower	5%	5%	5%	5%	10%	25%	25%	20%
Kalungwishi	0%	0%	0%	0%	10%	25%	20%	45%
Kabompo	0%	0%	0%	0%	0%	15%	55%	30%
Batoka gorge	5%	5%	5%	5%	10%	25%	25%	20%
Devil's gorge	5%	5%	5%	5%	10%	25%	25%	20%
New Gas	0%	0%	0%	0%	0%	40%	50%	10%
New Oil	0%	0%	0%	0%	0%	0%	90%	10%
New Coal	0%	0%	0%	0%	10%	25%	45%	20%
New Bio	0%	0%	0%	0%	10%	25%	45%	20%
New Solar CSP	0%	0%	0%	0%	0%	0%	10%	90%
New Solar PV	0%	0%	0%	0%	0%	0%	10%	90%
New mini hydro	0%	0%	0%	0%	0%	0%	10%	90%
New Hydro	0%	0%	0%	0%	0%	15%	55%	30%

Table D2. Total LCoE for all the supply technologies (in 2008)

	LCoE_Gen Cost (\$/MWh)	LCoE_T&D Cost (\$/MWh)	LCoE_Lost Elec (\$/MWh)	Total LCoE (\$/MWh)
Maamba Coal	62.4	16.8	19.2	98.4
Itezhi Tezhi	57.1	16.8	17.6	91.5
KNB Extension	36.7	16.8	11.3	64.8
Kafue G Lower	73.3	16.8	22.5	112.6
Kalungwishi	94.1	16.8	28.9	139.9
Kabompo	118.4	16.8	36.4	171.6
Batoka	44.7	16.8	13.8	75.3
Devils	45.1	16.8	13.9	75.7
New Gas	89.6	16.8	27.6	134.0
New Oil	156.4	16.8	48.1	221.3
New Coal	78.2	16.8	24.0	119.0
New Bio	80.0	16.8	24.6	121.3
New Solar CSP	208.4	16.8	64.1	289.3
New Solar PV	186.8	0.0	0.0	186.8
New mini hydro	201.8	0.0	0.0	201.8
New hydro	62.0	16.8	19.1	97.9

Note: Network distribution loss of 20.74% was used.

Table D3. Annualised system cost (in \$' million) for Base-Case system in an average scenario

	Avg gen Cost	Transm Cost	IndDist Cost	OtherDist Cost
2009	37.93	50.42	24.19	133.38
2010	57.98	55.82	27.89	144.96
2011	60.81	55.82	29.45	152.46
2012	133.10	58.02	31.01	138.64
2013	191.49	63.20	31.22	139.15
2014	210.02	66.58	34.24	153.22
2015	250.25	70.07	36.28	163.10
2016	434.48	74.41	33.93	152.17
2017	435.87	78.46	37.80	170.09
2018	451.99	82.52	41.08	185.44
2019	491.16	86.64	43.22	196.06
2020	531.64	90.90	45.37	207.46
2021	573.44	95.30	47.52	219.64
2022	614.81	99.65	49.63	231.82
2023	662.05	104.61	52.12	245.20
2024	709.76	109.60	54.56	258.96
2025	758.13	114.65	57.01	273.13
2026	816.78	120.19	59.95	284.02
2027	891.36	125.35	62.93	289.28
2028	972.51	131.42	65.73	305.49
2029	1 053.74	137.51	68.40	321.69
2030	1 135.77	143.72	71.03	337.85

Appendix E

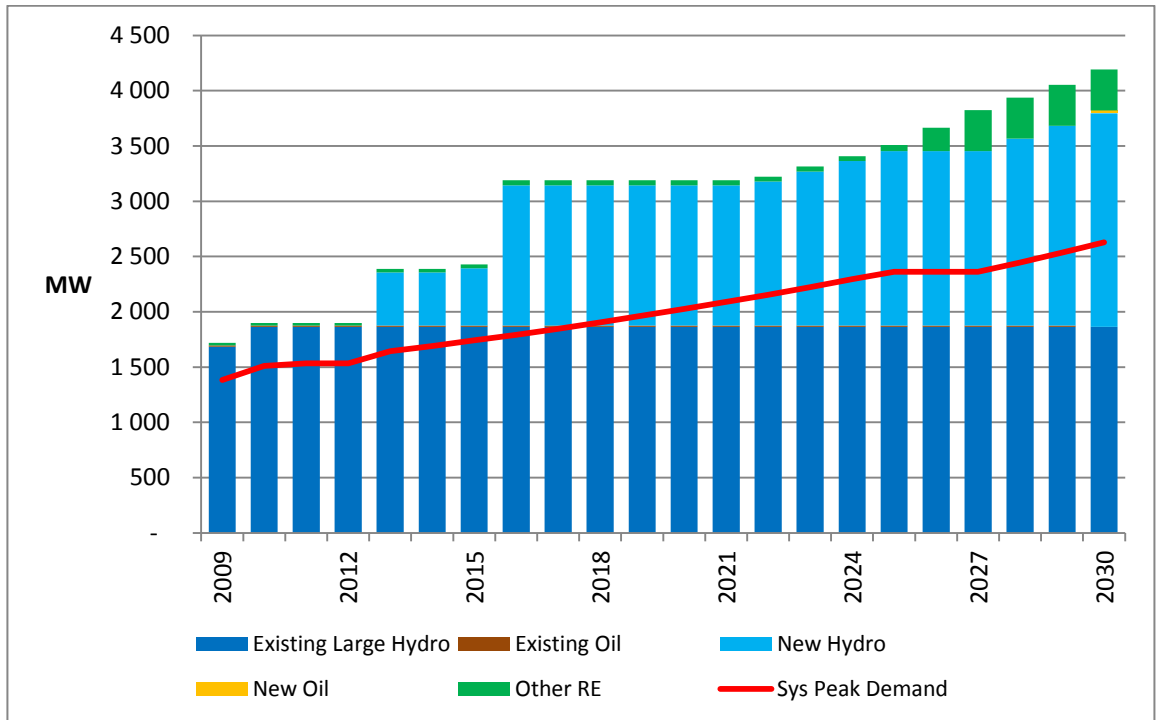


Figure E1. Total installed capacity for LG demand scenario in an average year scenario

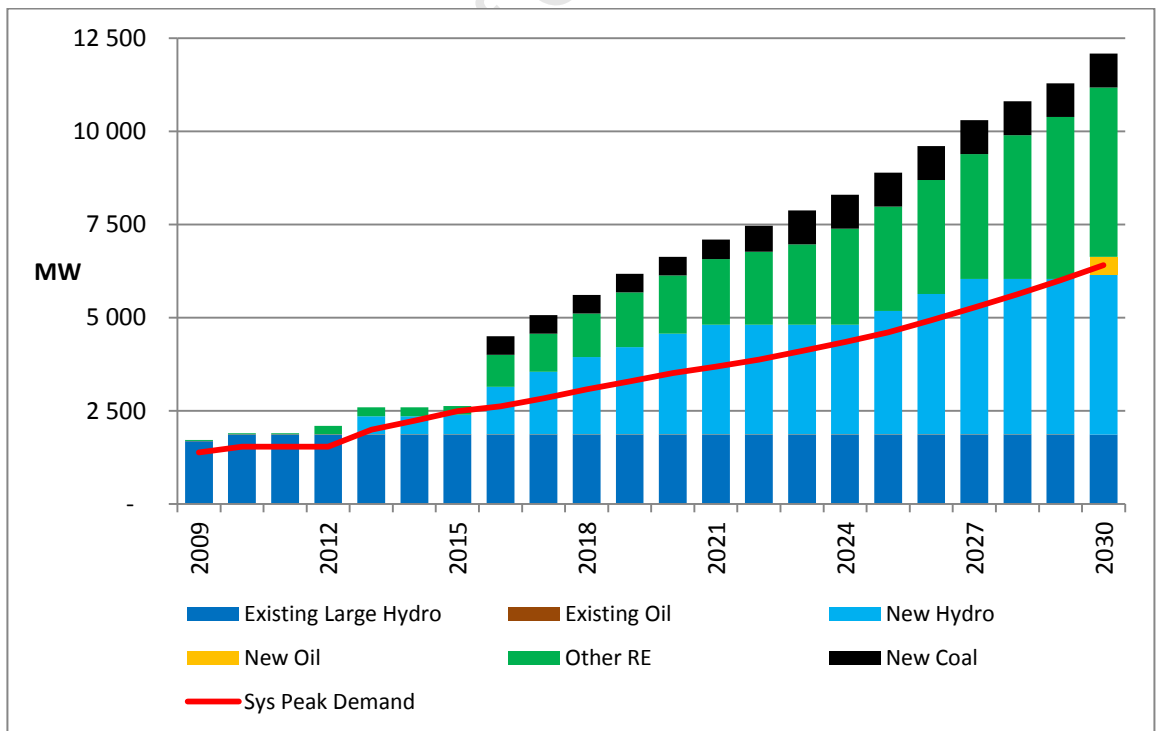


Figure E2. Total installed capacity with trade policy for HG demand scenario in a dry year scenario