Energy Investment pathways for sustainable future: A System Dynamics approach to solving the Electricity shortfall in Ghana

By

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Abstract

Ghana has been experiencing electricity supply deficit over the past decade. The annual gap between the electricity demand and supply has been a major concern in the country. Even though this challenge often seem temporary, it has never been fully resolved. The electricity gap in Ghana is attributed to underutilization of existing capacity, significant loss of power generated through transmission and distribution, low investment in the electricity sector, and low electricity tariffs.

A System Dynamics model is developed to create a vivid understanding of the complex feedback loops within the electricity sector through simulation. The results present an outlook of the electricity situation in Ghana and also indicate the ideal investment pathways for sustainable electricity supply in the future. The paper explores different policy options that could remedy this appalling situation from the standpoint of the government, the major stakeholder in the electricity production.

Given the low utilization factor of thermal and the limited sites for hydro, there is the need to consider solar as a possible roadmap to a fossil-free future. The declining cost of solar as a result of technological advancement coupled with the constant gas shortages for thermal plants makes solar ideal power source for future energy needs in Ghana. The government of Ghana should review the existing regulatory framework by liberalizing the electricity market to encourage private sector participation. A pricing system determined by free market activities will not only reduce government's debt on electricity subsidy but also offer an incentive for private investors.

Keywords: Electricity, Energy, Ghana, System Dynamics, Investment, and simulation.

Acknowledgements

"Every history has one quality in common with eternity. Begin where you will, there is always a beginning back of the beginning. And for that matter, there is always a shadowy ending beyond the ending." Edward Eggleston (1837 - 1902) - *The Circuit Rider.*

The beginning of this project was the beginning of works yet to begin and as it ends, I know it is not an end in itself but another milestone achieved in academia, for education is endless. Acknowledging the people whose efforts have granted success to this project, I wish to pay gratitude to the following:

First and foremost I express my gratitude to the Almighty God for guiding me through all the activities that led to the production of this work. His Grace has reached me abundantly.

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Finally, to my family and all others who provided me with all the support that could not be obtained in school, to them I say, your support is my strength and motivation, and may the portion of your reward be divine.

Tusen takk!!!

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1.0 Introduction

Energy is an essential sector of every economy. Different economic sectors; education, health, manufacturing, construction, among others are heavily reliant on energy to function (Ackah *et al.,* 2014). It is a paramount objective of government to institute measures that ensure sufficient provision of electricity for economic and social development (Winkler et al., 2011). Studies (Ferguson et al., 2000; Apergis and Payne, 2011) have established a positive correlation between electricity consumption and economic growth rates and development.

Ghana has witnessed considerable economic growth in recent times. In 2011, Ghana became one of the fastest growing economies in the world (approximately 14% growth rate). This has resulted in an increase in commercial demand and household consumption for electricity due to growth in industry and extension of Rural Electrification Project respectively. Since 2007, Akosombo hydropower, which supplies nearly 50% of the total electricity consumed in the country experienced significant decline in water level as a result of inconsistent rainfall patterns. Consequently, two of the four turbines in the dam have been shut down in 2014. The Thermal power sector has also failed to produce at maximum capacity due to frequent break-down of plants. The sector's capacity was heavily constrained in 2013 when a ship anchor severed the gas pipeline which transport gas from Nigeria to Ghana to power the Thermal plants. As regards, accessing constant and reliable electricity supply in Ghana for domestic and industrial activities has become a growing challenge. The country has experienced rampant load-shedding and erratic blackout. The shortage of electricity access is identified as a leading cause of low levels of economic and social development (Medlock, 2011).

Various projects have recently been instituted to deal with the electricity supply shortage in Ghana (Tema thermal power project 1 & 2, Takoradi Themal Plant Company, Takoradi International Company, and the West African Gas Pipeline). In the midst of the severe energy crises in 2007, the Ghana Energy Commission undertook an energy saving project that led to the distribution of free compact fluorescent bulbs to replace the high energy consuming incandescent bulbs. All public buildings were also fitted with capacitor to reduce public sector electricity consumption (Ghana Energy Commission, 2013).

These notwithstanding, the gap seem to be widening. Ghana's electricity market demand is forecasted to grow annually between 10%-15% (Acheampong et. al, 2014). The Energy-led-Growth-led-Energy hypothesis (Masih & Masih, 1997; Fatai et al, 2004; Ghali and El-Sakka, 2004; Akinlo, 2008), which asserts that there is bidirectional causality between energy consumption and economic growth could be attributed as the reason for the energy crisis especially given that Ghana has recorded significant economic growth (approximately 14%) recently (in 2011). Other arguments for the rising electricity demand and supply gap may be based on fluctuations in generation capacity due to seasonal factors (rainfall), power lost through transmission (obsolete and sub-standard equipment), distribution loss following ineffective electricity pricing system (fixed/regulated), as well as poor metering system (billing). There is therefore the need for strategic investment portfolio policies to address the incessant electricity gap in the country created by low power generation and increased consumption.

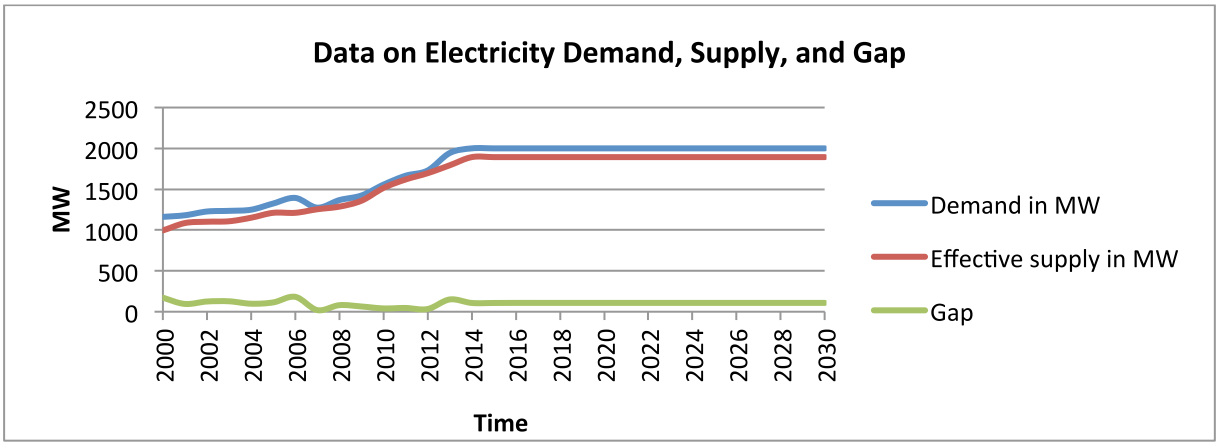


Figure 1: Annual electricity demand and effective supply between the period; 2000-2014

The figure above shows the total electricity demand and the effective electricity supply in Ghana. The effective electricity supply refers to the total capacity installed less the transmission and distribution losses as well as intermittent turbine shut downs as a result of low water level (in the case of hydro) and inadequate gas supply (for the thermal plants).

There are different studies that have been conducted (Gyamfi, 2007; Ackah *et al.,* 2014; Acheampong et. al, 2014) in Ghana concerning electricity issues. Most of these studies (Ackah *et al.,* 2014; Acheampong et. al, 2014) adopt an econometric approach. A deeper analysis of the structure and systemic layout of the Ghanaian electricity sector as well as the major parameters responsible for the electricity demand and supply gap has not been examined. An application of the system dynamic methodology for a deeper analysis of this dynamic phenomenon remains nonexistent.

The objective of this study is to assess the central dynamics that characterize the electricity sector in Ghana. It also sought to identify the ideal energy investment portfolios (and distribution policy) for addressing current electricity needs and ensuring a sustainable electricity provision for future demand in Ghana. The study discusses the implications of the current regulatory framework, market mechanism, and electricity pricing system on electricity demand and supply. The study also evaluates policy pertaining to post-generation/transmission losses on the demand and supply gap.

The study raises issues such as:

1. How is the electricity gap in Ghana developing?
2. What is the best energy source to solving Ghana's electricity challenges in the future?
3. What power investment choices should the government of Ghana adopt?

This presents a dynamic decision point for various stakeholders; the government of Ghana, and private energy companies that have earmarked Ghana as an investment destination. It also identifies leverage points for mitigating the persistent power challenges the country encounters annually.

A management simulation model that represents the structure of the electricity sector in Ghana is developed to provide insights on the sector dynamics and also inform stakeholders on possible trends of electricity demand and supply. The design of this simulation model is based on past and alternative future investment patterns of the three major electricity sources (hydro, thermal, solar) in the country.

The study explores and tests some policy options relating to the regulatory framework of the energy sector operations in Ghana. A policy of market regulated by demand and supply force referred to as the Automatic Tariffs-Adjustment Formula introduced by the Public Utilities Regulatory Commission (PURC) in 2011 is discussed as an alternative to the regulated market flooded with subsidies and full control. Different policies relating to investment portfolio (hydro, thermal, and solar) scenarios in electricity, power sources, market share, and price effect are also explored to identify the ideal policy options for current and future electricity demand/needs in Ghana.

The paper presents a quantitative and qualitative assessment of the dynamics of the electricity sector in Ghana. The first part (Introduction) identifies the research gap by stating the challenges that face the electricity sector in the future. It proceeds to state the objective and goals as well as research questions that help define the scope of the study. The second part is the theoretical background which highlights previous studies conducted in the energy sector. It examines the regulatory framework based on the concepts of system dynamics energy models to produce a brief and in-depth description of the energy sector. The third part describes the structure of the model developed to help understand the internal dynamics in Ghana’s electricity sector. It explains the main equations in the model. The forth section of the study presents the results based on the simulation. The outcome of the proposed policy options captured in the model is declared. The fifth section discusses the results from the simulation, the implications of the results, and how it relates to similar studies in the past. In the last part, conclusions are then drawn based on the discussion and recommendations made for both policy makers and future researchers on Ghana’s electricity sector.

2.0 Background/theory

Among the major challenges in the twenty-first century are increase in climate change and a gradual depletion in fossil fuel. The global oil consumption is expected to peak and start a gradual decline in the next twenty years (Randers, 2010). As more international treaties including the United Nations Framework Convention on Climate Change, the Kyoto Protocol, the Copenhagen Accord, and the Cancun Agreements respond to climate change issues (United Nations, 1998), the decline in the demand for fossil fuel could be even more rapid. The integral nature of energy in today's highly industrialized world has made it impossible to trivialize the repercussions of misplaced energy investment portfolio in the future. The need for consideration and diversification of investment to alternative energy sources beyond fossil is inevitable. The global economy is laying the foundation for the transition to a sustainable energy future. Issues of global warming, the quest for clean energy (Erdogdu, 2007), the desire for a stable macroeconomic environment and the need to reduce operational cost in the energy market is driving the energy investment decisions in this modern era.

2.1 Energy Transition

The global society is currently predominantly dependent on resource-limited fossil fuel. A sustainable energy transition would be a defining moment for society's sustainability in the future, ushering in an economy based on renewable energy flows from an economy based on fossil energy stocks (Sgouridis & Csala 2014). Energy transitions in the past have often been partial. Biomass is still a significant energy source (especially in developing countries) and exceeds nuclear energy notwithstanding the general belief that, the fossil fuel dominance has replaced the use of biomass (International Energy Agency, 2013). This is similar to the case of the transition from coal to petroleum and natural gas. These transitions took over a century of innovation and diffusion for scale sufficiency (Fourquet, 2010). Energy transitions follow the s-curve technology diffusion pattern that consist of an experimentation phase followed by the dominance stage as a result of universal adoption, steady stage through standardization, then the emergence of network externalities, saturation, and possible phase-out (Christensen, 1997; Wilson & Grubler, 2011). Grubler (2012) also observed that the downstream demand of energy is higher than the upstream supply. This implies that, the upstream supply services on one hand, can spearhead energy transition and the downstream energy demand stock on the other hand may exert a lock-in effect on the energy supply.

2.2 The Regulatory Framework of Ghana's Electricity Sector

The Public Utilities Regulatory Commission (PURC) was established by the Public Utilities and Regulatory Commission Act, 1997 (Act 538). The Public Utility Regulatory Commission (PURC) and the Energy Commission are the regulatory bodies in the energy sector in Ghana. The PURC is responsible for setting electricity tariffs. This is often done in consultation with key stakeholders made up of the electricity generators, distributors and the representatives of major consumers. The Energy Commission is responsible for technical regulation. In 2006, it established a licensing framework for licensing electricity service providers. The Licensing Manual for service providers in the electricity supply industry sets the requirements and guidelines for entities desiring to acquire licenses to operate in the electricity supply industry. Provisional and full licenses have been issued to entities engaged in the various segments of electricity supply. Besides adding generating capacity to existing capacity and enhancing service delivery to customers, the licensing regime enhances the Commission's authority to hold the licensees to terms defined in the license.

Table 1: Energy production applications issued with licenses

Expression of Interest in Renewable Energy Investment in Ghana		
Renewable Energy Technology	**Number of Applications issued with Production License**	**Total Capacity**
Solar	29	2,155 MW
Wind	4	676 MW
Waste-to-Energy	3	271 MW
Hydro	3	195 MW
Wave	1	1,000 MW
Biomass	2	60 MW

Table 1 - Source: Ministry of Energy 2014

The table above shows some of the licenses that have been issued by the Energy Commission to various private independent power producers to invest in different energy portfolios. The electricity situation would be solved is all these licensed projects are effectively executed.

2.3 Structure of the electricity sector in Ghana

There are four main state organisations involved in the electricity supply chain in Ghana. The Volta River Authority (VRA) is responsible for generating electricity. After power is generated, the Ghana Grid Company (GRIDCo) takes charge of transmitting the power generated through the grids. Two organisations; the Electricity Company of Ghana (ECG) and the Northern Electricity Department (NED) distribute the transmitted power to the final consumer. Ghana's electricity production is based on three main sources: Hydropower (water from dams), Thermal (gas, Light Crude Oil, Distillate Fuel Oil), and Solar. According to the Volta River Authority (VRA), the total installed capacity is 2,814 Megawatts (MW) whiles the effective capacity stood at 2,492 as of December 2013. About 57% of this supply is from hydropower and approximately 42% resulting from thermal plants powered by oil and natural gas. The remaining 1% is made up of solar photovoltaic (PV) and other renewables such as biomass. Figure two below presents an overview of the major parties involved in the electricity sector in Ghana, from generation to consumption.

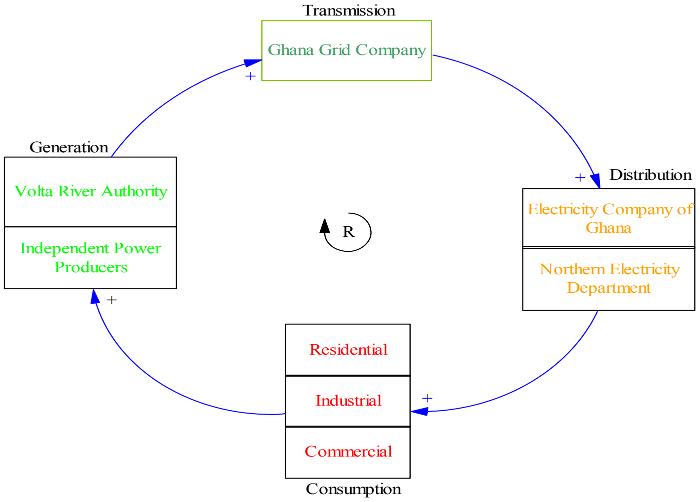


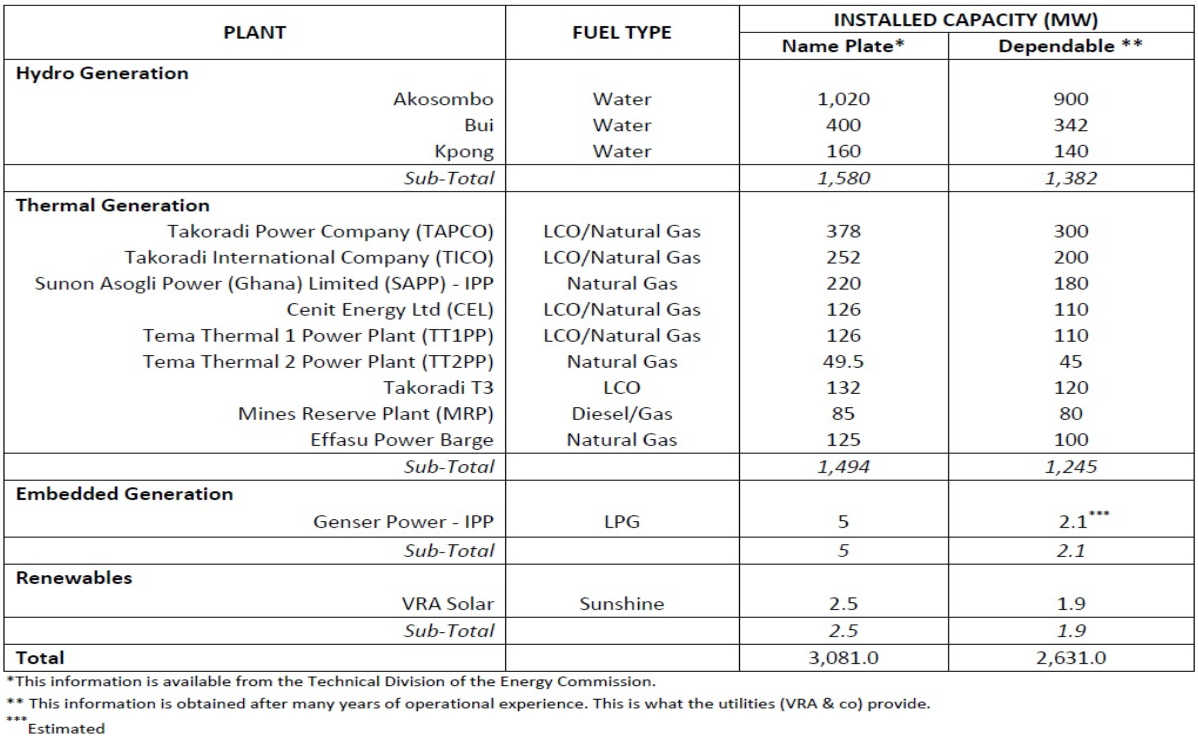
Figure 2: Organisations and functions within Ghana's Electricity sector

Figure 1 above indicates the state institutions involved at each state of power production and supply to the final consumers.

2.4 Electricity Supply and Demand in Ghana

Ghana's Energy Policy from 2010 sets out to increase the share of renewable energy in the national energy mix, through focusing on improved efficiency of fuelwood use, as well as shifting from use of biomass to use of other alternative renewable energy sources, such as wind and solar. Currently, the share of modern renewables in the energy mix is insignificant (Ministry of Energy, 2011). The energy sector goals include increasing installed capacity from about 2,000 MW to 5,000 MW by 2015, and establishing universal energy access by 2020 (Ministry of Energy, 2010). Renewable energy will therefore play a significant role in maintaining reasonable emission levels. The current strategy aims to increase the renewable energy share in the country's electricity mix to 10% by 2020 (Ministry of Energy, 2010). As at 2010, the installed electricity production in the country had reached 2,185.5 MW, with 1,865 MW available (Energy Commission of Ghana, 2011). Most of the generated power in 2010 came from hydroelectric sources and accounted for nearly 70%, with 30% generated from thermal power. Electricity demand in the country is estimated to be growing at a rate of 10% per year in 2012 (Ministry of Energy 2012). The government estimates that at this growth rates, it would be necessary to install an additional 200 MW capacity every year, in order to meet the demand.

Table 2: Capacities of different power plants in Ghana



PLANT	FUEL TYPE	INSTALLED CAPACITY (MW)	
		Name Plate*	Dependable **
Hydro Generation			
Akosombo	Water	1,020	900
Bui	Water	400	342
Kpong	Water	160	140
Sub-Total		*1,580*	*1,382*
Thermal Generation			
Takoradi Power Company (TAPCO)	LCO/Natural Gas	378	300
Takoradi International Company (TICO)	LCO/Natural Gas	252	200
Sunon Asogli Power (Ghana) Limited (SAPP) - IPP	Natural Gas	220	180
Cenit Energy Ltd (CEL)	LCO/Natural Gas	126	110
Tema Thermal 1 Power Plant (TT1PP)	LCO/Natural Gas	126	110
Tema Thermal 2 Power Plant (TT2PP)	Natural Gas	49.5	45
Takoradi T3	LCO	132	120
Mines Reserve Plant (MRP)	Diesel/Gas	85	80
Effasu Power Barge	Natural Gas	125	100
Sub-Total		*1,494*	*1,245*
Embedded Generation			
Genser Power - IPP	LPG	5	2.1***
Sub-Total		*5*	*2.1*
Renewables			
VRA Solar	Sunshine	2.5	1.9
Sub-Total		*2.5*	*1.9*
Total		3,081.0	2,631.0

*This information is available from the Technical Division of the Energy Commission.

** This information is obtained after many years of operational experience. This is what the utilities (VRA & co) provide.

***Estimated

Table 2 - Source: Ministry of Energy 2014

Hydro

Hydropower already constitutes the majority of electricity production in Ghana. Akosombo and Kpong hydropower stations provide a total of 1,180 MW of electricity, corresponding to 60% – 70% of the total electricity requirements. A 400 MW Bui hydropower plant is currently under development at Bui and has started producing up to 30% capacity. There are still potential hydro power sources in the country. The Ministry of Energy has identified about 21 potential mini-hydro sources with capacities ranging from 4 kW to 325 kW (and a total capacity of 840 MW) (*Ministry of Energy, 2010)*. The total potential undeveloped hydro capacity in Ghana is estimated to be about 400 MW.

Solar PV

The national target for renewable energy is to achieve 10% renewable energy share by 2020. The exploitable solar power potential has been identified as 20 MW (Ministry of Energy, 2011*)*. VRA has installed a 2-megawatt-peak (MWp) solar photovoltaic (PV) grid-connected plant as a pilot project in Navrongo in the Northern Electricity Distribution Company (NEDCo) areas of operation. Four sites have also been earmarked for a total of 10-MWp PV plants.

Blue Energy, a renewable energy company based in the United Kingdom agreed to build the biggest photovoltaic (PV) and solar energy plant in Africa. The project dubbed; the Nzema project would be based in Ghana and provide electricity to more than 100,000 households (Vaughan, 2012). Installation of about 630,000PV modules was set to begin late 2013 with first electricity generation in 2014. The project, when completed, is expected to add a total of

155 MW of power to the current capacity which will result in an increase of 6% of total power supply (McGarath, 2012). This initiative is very essential if Ghana is to reach its renewable target from the current 1% to 10% by 2020.

Thermal

This is the second largest source of electricity in the country after hydro. Government quite interested in improving g the thermal capacity in the country. Whiles this might be beneficial now, investment should also focus on improving more efficient, sustainable and environmentally friendly alternatives such as solar. There are about eight major thermal plants in Ghana currently whiles plans are still underway to develop more. The most prominent amongst them are the Tema thermal power project 1 & 2, Takoradi Themal Plant Company, Takoradi International Company.

Wind

The average wind speeds in Ghana show possibilities for wind power project development along the eastern coastal areas, as well as the mountains along the south-eastern corner of the country. The National Energy Sector Strategy sets to increase the share of renewable energy through facilitation of renewable energy harnessing, part of which would be wind power development. The estimated gross wind power potential is 5,600 MW, representing 1,128 km2 of land (Ministry of Energy, 2011*)*. The estimated exploitable potential is set at 200-300 MW. There is a wind power project which has a total capacity of 50 MW.

Biomass & biogas

Biomass is Ghana's dominant energy resource in terms of its endowment and consumption. Rural communities that have yet to receive connection to the national grid, use biomass as the main source of energy. Approximately, 20.8 million hectares of 23.8 million hectare land mass of Ghana is covered with biomass resources. Biomass fuels in Ghana mainly comprise of charcoal, plant residues and wood fuel. Wood fuel is the major form of biomass used as energy source for both domestic and commercial purposes in Ghana; about 90% of rural households depend on wood fuel and other biomass resources for domestic purposes. Wood fuel is the dominant and cheapest fuel available on the Ghanaian market; the production, transportation and sale of wood fuels are all undertaken by the private sector.

The problem of energy investment is complex and important. Even though different studies have been conducted in the energy sector highlighting the looming challenges of over reliance on fossil energy (Randers, 2010; Humphreys, 2014), and also addressing global energy issues, very little studies address the different investment scenarios to bridge power supply gap in Ghana. No study in the extant literature adopts the system dynamics methodology to create a fundamental structure of the Ghanaian energy sector for detailed analysis. Based on the trend of global energy demand, the rate of shifting dominance between fossil and renewable energy, and emergence of renewable energy amongst competitive energy technologies, different investment policy options are evaluated in this study. The study also proceeds to evaluate policies related to price, and post-production losses (transmission and distribution) which are very significant in the case of Ghana.

3.0 Model

The application System Dynamics modelling methodology in energy research is not novel. Besides its application in energy market dynamics and economic indicators (Naill, 1977), System Dynamics is used by different studies (Chi, et al., 2009; Connolly et al., 2010) to conduct simulations for energy development and energy structure testing. It is also applied in studies such as Anand et al., (2005) and Feng et al., (2013) who studied the environmental aspect of energy and CO2 emissions. Issues of energy security resulting from supply and demand in country specific cases have also been examined by Wu et al., (2011) and Shin et a., (2013).

None of the studies on energy in Ghana to the best of my knowledge adopts the System Dynamics Approach which first underscores the fundamental complexities of a system and evaluates possible scenarios through simulations to prescribe potent blueprint for sustainably secure energy future in the country. A system Dynamics model is therefore ideal in many relative terms for understanding such endogenous dynamics.

The simulation software, iThink, version 10.0.6 was used to constructed the model and conduct all simulations. To improve readability of the figures, the results of the simulation were exported to excel and the graphs constructed and transferred to the main thesis report. The simulation results presented in graphs and tables are detailed and easy to read and interpret.

The central focus of the model is to create a structure that represents the electricity sector in Ghana. This provides insight on the internal dynamics creating the persistent power crises and also makes it easier to identify police leverage point to rectify the problem. The model also sets to determine the investment for future capacity demands. The simulation period is 31 years. This is decided based of the historical period under consideration. It is often advised that, one should look as far back as one looks forward. The simulation period starts from 2000 to 2030.

The major stakeholder that this model most appropriately serves is the Government of Ghana and to an extent, independent power producers (private investors) who identify Ghana as a prospective energy investment destination. Needless to say, that an improvement in the power situation in Ghana positively affects the citizens and other entities that are not directly connected to the power sector.

From the government's perspective, the model provides a better understanding of the underlying causes of the electricity crises but most importantly the major contributing factors which when addressed/leveraged can result in a much larger improvement. Investors can review the simulations and analysis from the model to understand the trend of demand for the different power sources. This offers a sense of direction for their future investments.

The model also includes the electricity pricing sector. In Ghana, this falls under the jurisdiction of the Public Utilities Regulatory Commission. Currently, tariffs are determined by this regulatory body from time to time. The study assesses the effect a liberalized market would have compared to this ‘fixed-term’ pricing system. A liberalized electricity market will not only reduce this burden, issues of subsidy could also be addressed through that.

3.1 Model Structure

The model structure is informed by empirical studies that have examined the major factors accounting for electricity demand and supply gap and the dynamics of energy investment and portfolio diversification such as Humphreys (2014). It takes into account the major power source for electricity production, the investment made in these sectors, the price of electricity, and the demand over the period under consideration.

3.1.1 The Electricity Supply Sector

The Electricity supply sector in Ghana connected to grid consists of three main power sources; hydroelectric power, thermal power, and solar PV. In terms of off-grid power consumption, biomass is the leading energy source. Off-grid supply is however not the focus of this study.

Hydroelectric Power: The model contains the hydropower sector which is made up of three main sources: Akosombo hydropower, Kpong hydropower, and Bui hydropower. These together constitute about 50% of electricity produced in the country. The first hydro plant was built in 1965. The facility has since received improvements in capacity as the electricity demand increased over time. The current capacity stands at 1,020 megawatts. Since 2000, other hydro plants have been built to cater for the growing power needs. These were the Kpong hydro power which has a total installed capacity of 160 MW, and the Bui Hydro project which has a total capacity of 400 MW. Collectively, these hydro power sources make up 53.8% of the total installed power capacity as of 2013 (Ghana Energy Commission, 2013). The Energy Commission also projects a potential undeveloped hydro capacity of 195 MW from three water sources. Even though there are other potential sites for developing hydro plants, they are mini capacity projects, the sum of which is less than half the current operating capacity. The total hydro capacity potential in Ghana is therefore limited. The productivity of the hydro source is mainly resource (water) constraint.

The hydro capacity is shown the stock and flow diagram in *figure 3* below. The structure starts with the stocks of total hydro capacity installed and capacity under construction. When construction is completed after a construction time of 5 years, the plant becomes ready for use and the capacity is therefore added to the installed capacity. The capacity installed is depleted by the rate of depreciation over time. The hydro constructed increases by the hydro project initiation rate. The hydro initiation rate is the total annual amount of investment (in Ghana cedis) allocated to hydro projects. This amount is then divided by the unit cost of installing a MW of hydropower. Initially, the unit cost was set constant but increases slightly with challenges that affect the hydro production. The hydro plants depend on rainfall for them to function to capacity.

As a result of seasonal rainfall inconsistencies, water level in the dam is often below capacity. Some hydro turbines are therefore shutdown especially during certain seasons of the year, reducing the utilization factor, which represents the percentage of installed capacity actually generating power. Akosombo dam, the largest source of electricity supply suffers this setback of low utilization as a result of low water level the most and produces below capacity. The average production potential/utilization factor of hydro, which depends on rainfall, is ninety percent (90%). The annual water level of the dam from 2008 - 2013 is displayed in the figure below.

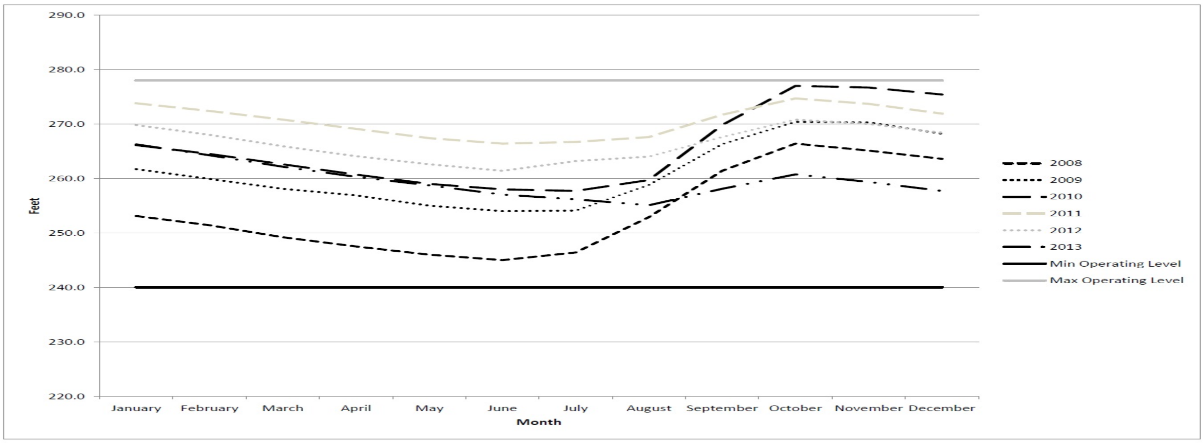


Figure 3: Annual water level in Akosombo dam

The rainfall pattern determines the utilization factor for hydro since the number of turbines operating at a time depends on the water level. Most of the hydro shutdowns are often water related rather than damage and maintenance. The utilization factor in the model is therefore equivalent to the rainfall pattern. The product of the utilization factor and the total hydro capacity installed is the Effective hydro capacity (power generated) hence,

$$Ehc = (ufh * Ihc,$$

Where *htc* is the Effective hydro capacity, *ufh* is the utilization factor for hydro, and *Ihc* is the hydroelectric power capacity installed. The hydro capacity installed changes with the hydro depreciation rate and hydro project completion rate. The hydro depreciation rate is, $Hdr = (Ihc/hlt)$, where *Hdr* is the hydro depreciation rate, and *hlt* is the hydro lifetime which is hundred years. The hydro project completion rate (*Hcr*) is given by: $Hcr = (HC/ht)$, where *HC* is the Hydro capacity under construction, and *ht* is the hydro construction time which is three years.

The hydro capacity under construction depends on the hydro project initiation rate, which is a function of the average hydro cost per MW and the total amount of investment in Ghana cedis budgeted for hydro projects. The equation hydro project initiation rate is therefore: $(Hp = Hi/Ch)$, Where *Hp* is the hydro project initiation rate; *Hi* is the Hydro investment in cedis; and *Ch* is the Actual Cost per MW Hydro. The actual cost per MW hydro is a function of the initial cost per MW hydro (Init Ch) and the effect of rainfall relative to dam capacity on MW cost hydro. The actual cost per MW hydro is given by:

$$Ch = Init\ Ch * (1 + eRf)$$

Where *Ct* is the Actual Cost per MW hydro (*Init Ct)* is the Initial cost per MW hydro, and *eRf* is the Effect of rainfall/dam water level on cost MW of hydro. As the dam water level increases, the operational cost decreases with the effect of rainfall. The effect of rainfall effect is given as: $eRf = (1 - Rf)$ where *Rf* is the average annual rainfall/dame water level.

Thermal Power: The thermal sector is the second major source of electricity. It has a total installed capacity of over 40% of total electricity consumed. Similar to the hydro power, this also has its own limitations. All of Ghana's thermal plants depend on gas. Most of the gas is supplied by Nigeria through the West African Gas Pipeline. The effective thermal capacity therefore depends on the availability of gas. When there is limited gas supply, the thermal facility utilization factor is below 1. Another thing that affects the thermal utilization is the investment in solar. As more solar PV (with increasing returns) is constructed, its substitute (thermal) becomes less attractive over time.

Thermal construction in Ghana began in the late nineties as electricity demand increases and the hydro capacity became overburdened. Most of the thermal capacity on Ghana was constructed after 2000. The initial thermal capacity as of 2000 is 100 MW. The stock of installed capacity of thermal depends on the thermal depreciation rate and the thermal project completion rate. Thermal depreciation rate (*Tdr*) is given as $Tdr = (Itc/tlt)$ where *Itc* is the Thermal capacity installed, and *tlt* is the thermal lifetime. The thermal project completion rate is a function of the thermal capacity under construction and the construction time, which is two years. The equation of the thermal completion rate is given by: $Tcr = (TC/tt)$, where *Tcr* is the Thermal project completion rate, *TC* is the Thermal capacity under construction, and *tt* is the Thermal construction time which is two years.

The stock of thermal capacity under construction depends on the thermal project initiation rate, which is a function of the average thermal cost per MW and the total amount of investment in Ghana cedis allotted to thermal. The equation of the thermal project initiation rate is given by: $(Tp = Ti/Ct)$, Where Tp is the Thermal project initiation rate; Ti is the Thermal investment in cedis; and *Ct* is the Actual Cost per MW Thermal. The actual cost per MW thermal is a function of the initial cost per MW thermal and the effect of gas availability on MW cost. The actual cost per MW thermal is given by:

$$Ct = Init\ Ct * (1 + eAg)$$

Where *Ct* is the Actual Cost per MW thermal; *Init Ct* is the Initial cost per MW thermal, and *eAg* is the Effect of gas availability on cost MW thermal. As the gas availability increases, the operational cost decreases with that effect. The effect of rainfall effect is given as: $eAg = (1 - Ag)$ where *Ag* is the availability of gas. This is equivalent to the utilization factor. It is the same as the utilization factor is plant redundancy is not as a result of damage. The total effective capacity is the product of the utilization factor and the total installed capacity.

$$Etc = (uft * Itc)$$

Where *Etc* is the Effective thermal capacity, and *uft* is the utilization factor for thermal. In recent times, Ghana's thermal faces gas shortages. There is inconsistency in supply forcing some of the plants to be shut down. Increasing the number of thermal plants/capacity seemingly compounds the problem.

Solar PV: Solar PV is another growing energy source in Ghana. It is one of the little renewable energy that is reliable. Government has undertaken some pilot projects in the field of solar to supplement the energy shortfall. In the long-run, it could become the leading energy source. It is however at the moment limited by cost and development in solar technology compared to other major energy sources. The solar power could tend to have a negative correlation with the hydro. As the dam water levels decline during the dry season and turbines are shut down leading to lower utilization factor, Solar could emerge as an ideal substitute because it would have a higher utilization factor with warmer and sunny weather that characterizes the dry season. The total effective capacity is the product of the utilization factor and the total installed capacity. The effective solar capacity is given by:

$$Esc = (ufs * Isc)$$

Where Esc is the Effective solar capacity, ufs is the utilization factor for solar, and Isc is the solar capacity installed. Solar utilization factor is relatively equivalent to hundred percent unless damages occur on capacity installed, since the conditions in Ghana are favorable for all year solar production. The installed solar capacity is dependent on the solar project completion rate (Scr), which is a function of the solar capacity under construction (SC) and the solar construction time (st), which is three years: $Scr = (SC/st)$.

The solar capacity under construction is a function of the solar project initiation rate given by the equation: ($Sp = Si/Cs$), where Sp is the solar projects under construction, Si is the annual investment in Ghana cedis allocated for solar production, and Cs is the cost per MW of solar unit. Contrary to thermal, the cost per MW solar is expected to decline over time with the effect of learning improving technology and efficiency. The cost per MW solar is:

$$Cs = Init\ Cs * (1 * le)$$

Where Cs is the Actual Cost per MW solar; $Init\ Cs$ is the Initial cost per MW solar, and le is the Effect of learning curve on cost per MW solar. The effect of learning *(le)* is given as ($1-lc$), where lc is the learning curve. As the learning curve grows, the learning curve effect on cost becomes lower and the multiplier effect on the cost unit of MW solar becomes smaller. Learning curve is an essential part of the model as it determines the solar adoption rate.

The Learning curve

Different studies (Moxnes, 1992; Wang et al., 2012; IRENA, 2012) on output effect on learning curve and Solar PV technology valuation assume price reduction consistent with cumulative production. Indeed, the real reason for capacity decline might not be related to learning. That notwithstanding, the curve is reflective of the capacity development over time. Solar cost is expected to decline over time as a result of the learning curve effect. This will result in increasing returns on solar investment. One of the features of technology which provides increasing returns is the large set-up (initial) cost, learning effects, co-ordination effects, and self-reinforcing expectations (Arthur, 1988).

Evaluating PV technologies with single-factor learning curve would likely result in overestimation of the effects of learning-by-doing (Chanwoong and Junesuek, 2014)). A solar PV valuation that adopts a two-factor learning curve; cumulative production and technological innovation driven from Research and Development (R&D) reduces the estimation deficiency of the single-factor learning curve applicability especially in technologies where R&D leads to rapid technological change (Kouvaritakis et al., 2000). Subsequent studies on renewable energy cost/price estimates (McDonald and Schrattenholzer, 2001; Kobos et al., 2006) supported the two-factor learning curve framework by incorporating it in their evaluations of learning curve. This study considered a learning curve driven from the accumulated production of solar and the R & D. The solar capacity is therefore not directly linked to the learning curve. Instead, a learning curve based on similar studies that accounted for detail variables such as knowledge stock, depreciation, and R & D time lag (Kobos et al., 2006) is adopted. The learning curve in this study is illustrated in the graph below:

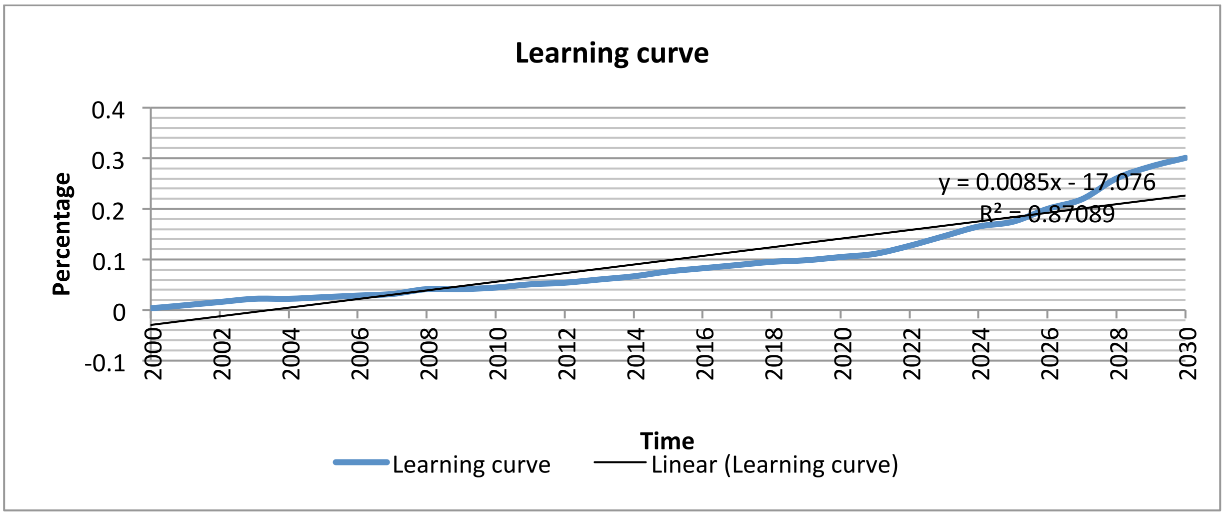


Figure 4: Learning curve

The learning curve pattern in this study is derived from the findings of previous studies, which found relatively similar pattern of learning curve using the two-factor analysis. Kouvaritakis et al., (2000), deduced a cumulative production effect of 16% and R & D effect of 7%. A similar result was arrived at by Criqui et al., (2000) who found 16.4% and 4.4% respectively. In a subsequent study by Miketa and Schrattenholzer (2004), the learning by doing rate of 9.7% and learning by searching rate of 10% was illustrated.

The complete structure of the electricity supply sector comprising the three major energy sources discussed above is illustrated in the stock and flow structure below:

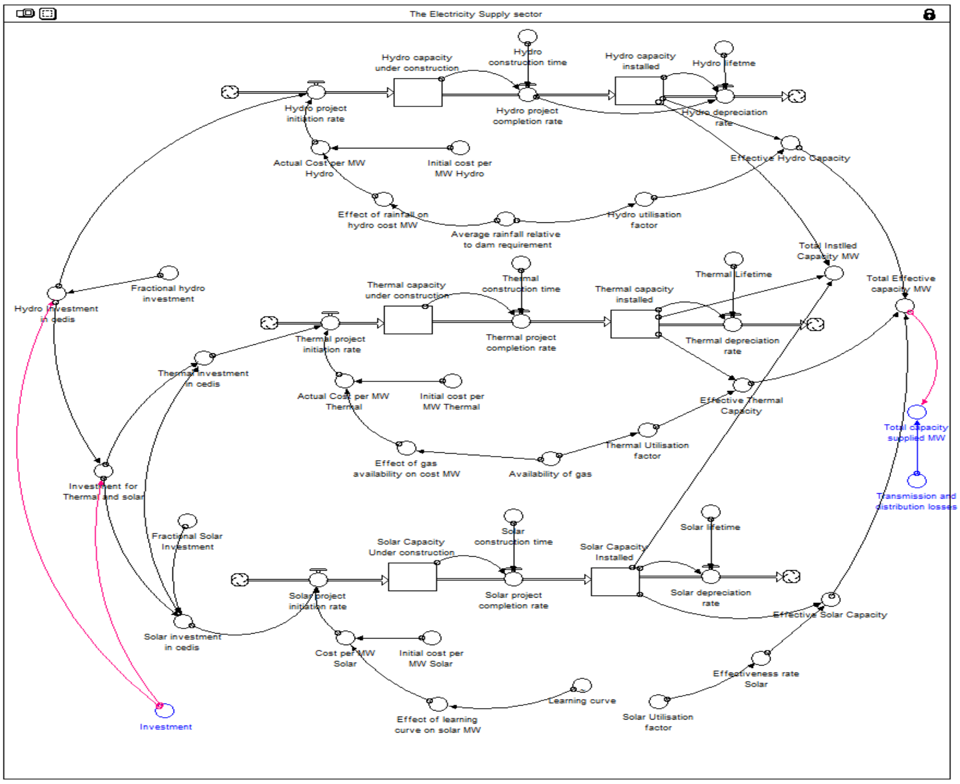


Figure 5: Stock and Flow diagram of the Electricity Supply sector

3.1.2 The Electricity Demand Sector

The electricity demand in Ghana has witnessed considerable growth. Whiles this is attributed mainly to economic growth and expansion of industrial (mining, construction, etc) activities, there has also been a considerable extension in the grid connection. The execution of the rural electrification project contained in the Strategic National Energy Plan resulted in a direct increase in the demand for electricity. The fact that there was a gap prior to the enforcement of this policy in the last decade aggravated the demand supply gap as more strain is place on supply.

The indicated demand

Different energy researchers have estimated electricity consumption using different methodologies. Ranging from the widely used reduced-form model of Engle and Granger (1987), to the structural form model of Kokkelenberg and Mount, (1993), and the Genetic Algorttm of Ceylan and Ozturk (2004), the electricity demand in this study is determined by the indicated demand. The word "demand" is used here cautiously because, the demand does not necessary refer to what is consumed but rather the electricity required. In the event of electricity shortage which is the case in recent times, the electricity consumed is equivalent to the total effective electricity supplied/distributed. The indicated demand is a function of demand, price, annual growth, and the price elasticity. The equation for indicated demand in the model is given by:

$$Init\ D * (1 + g) * gt * ((P/P0)^{PE})$$

Where: *Init D*: is the Initial Demand in the year 2000. The amount of electricity demanded in 2000 according to historical data is 1161 MW. This represents the initial demand at the beginning of the simulation. The demand growth rate is denoted by *g,* which is 6%. The historical growth of demand, *gt*, is averaged at 6%. *P,* is the current price of electricity. *P0*, is the reference electricity price which is adjusted to the electricity price over time. *PE*: represents the price electricity of electricity. In Ghana, the price electricity of demand is -0.38. This means that a percentage change in price will lead to a more than proportionate change in electricity demand. The simulation results of the indicated demand can be seen in figure 17. The variables of indicated demand can also be seen in the stock and flow diagram of the demand sector in figure 4 below.

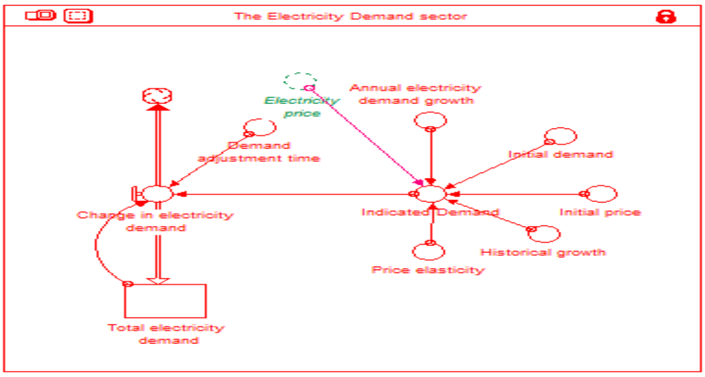


Figure 6: Stock and Flow diagram of the Electricity Demand sector

The demand for electricity is given by:

Total_electricity__demand(t) = Total_electricity__demand(t - dt) + (Change_in_electricity__demand) * dt

Where, demand increases or decreases every time step according to the development of the indicated demand. As seen in the structure above, the demand is adjusted to the indicated demand.

3.1.3 The Electricity Price Sector

The electricity price is another aspect that is very essential in the model. Currently, the electricity price in Ghana is fixed by the Public Utilities Regulatory Commission over a period of time. Prices are barely reviewed unless there is a huge global price change. The electricity in Ghana is mainly supplied by the government as the regulatory framework limits private sector participation. This has resulted in price stagnation most of the time which is not reflective of the indicated market situation. The electricity price is given by:

$$P = P0 * (ds)^{Ps}$$

Where: *P* is the Electricity price and *P0* is the reference electricity price as represented in the indicated demand formulation. Then, *ds* represent the demand/supply ratio and *Ps* denotes the price sensitivity of the demand and supply ratio. The ds and the *Ps* are accountable for the price dynamics. Unlike the indicated demand, the price sensitivity has no direct effect on the electricity supply because the market is not liberalized. When $ds > 1$, it means the demand exceeds the supply and the price sensitivity determines the electricity price. In Ghana; *Ps* is 0.8 ($Ps < 1$). This implies that, the electricity price is lower than the indicated price in a free market. A $Ps = 1$ means the price does not respond to the interaction of demand and supply. On the other hand, $Ps > 1$ means the price is significantly high and demand exceeds supply in the free market. The effect of different *Ps* values between 0 and 2 can be seen in figures under the sensitivity analysis section.

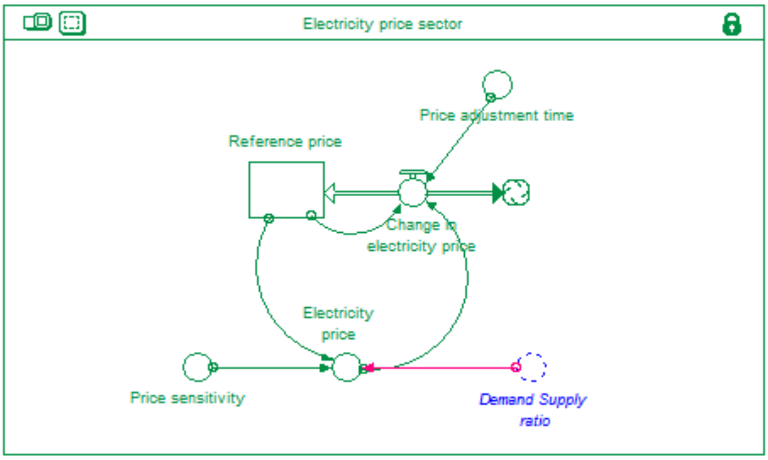


Figure 7: Stock and Flow diagram of the Electricity Price sector

The figure above represents the structure of the electricity price sector in Ghana without any direct effect on the supply. It must be noted however that, price does have an effect on supply through the demand. As *Ps* increases, demand decreases and that results in a decline in *ds* and subsequently and decrease in investment.

3.1.4 The Electricity Investment Sector

Investment made in the electricity sector accounts greatly for the current available capacity. The annual investment made in the electricity sector before 2014 is not readily available. Calculations of the annual investment were conducted based on the total amount of megawatts of power installed over the simulation period and the average unit cost of a megawatt. The results arrived at was taken as the average investment in cedis made in the electricity sector from 2000 – 2014. Thereafter, the investment is calculated based on the demand and supply gap and the fraction of GDP that represents the electricity sector investment. The amount of cedis investment in the electricity sector is distributed to the various power sectors. The ratio of distribution was based on data from the Energy Commission.

The amount of funds made available for investment in the electricity sector depends on the demand and supply gap. The gap is the difference between the demand and the total electricity distributed to consumers and accounted for. The amount of power distributed is the difference between the total effective capacity and the transmission and distribution losses. The demand supply gap in megawatts is multiplied by the average cost per MW of power installation to arrive at the budgeted investment in cedis:
*Budgeted_Investment_in_cedis = Demand_Supply_gap*Average_cost_per_MW_unit*

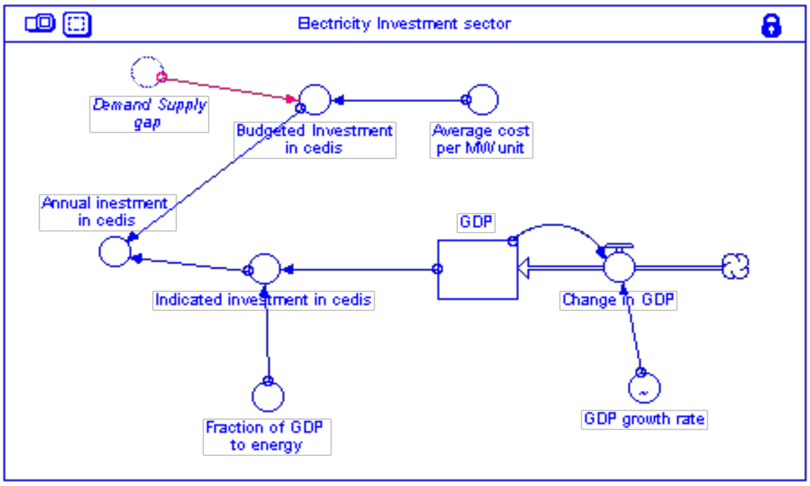


Figure 8: Stock and Flow diagram of the Electricity Supply sector

The indicated investment on the other hand does not depend directly on the demand and supply gap but rather the trend of GDP. A constant fraction of 1.5% is estimated to be the annual investment needed in the electricity sector. The indicated investment therefore increases according to GDP:
*Indicated_investment_in_cedis = Fraction_of_GDP__to_energy*GDP*

The annual investment in cedis is therefore a function of the indicated investment and the budgeted investment:
MIN(Budgeted_Investment_in_cedis,Indicated_investment_in_cedis)
This annual investment in cedis is apportioned between the three power sources: hydro, thermal, and solar. Initially, a constant proportion is assumed for both over the historical period based on the capacity installed within such period. Hydro is the ideal source of

electricity production in Ghana. Unfortunately, the potential hydro sites are limited. The divestment of investment became inevitable. There are two main investment pathways for hydro; low investment scenario where no more hydro capacities are developed because they are small sites used as tourist venues, and the high investment scenario where the highest undeveloped remaining hydro potential of 400 MW is developed. The remaining investment after hydro is then shared between thermal and solar. Based on the installation over the period, the fraction of solar was about 1% of remaining investment after hydro and the rest was invested in thermal. This fraction however changed as the challenges in thermal become more apparent and the cost of solar declines. The new fraction of investment in solar was therefore model as a logistic function.

The investment in Ghana cedis of hydro is given by:

Historical_Hydro_investment_in_cedis(1-Hydro_investment_switch)+Current_hydro__investment_in_cedis*Hydro_investment_switch,*

Where the historical investment is the annual hydro investment from 2000 – 2013, which is the annual investment multiplied by the fraction allocated to hydro (*Fractional_hydro__investment*Average_Annual__Investment*). The fraction hydro investment is 40%.

The current hydro investment is the investment in Ghana cedis after 2014. This is given by :

*0+ STEP(Desired_Hydro__installation_MW*Actual_Cost_per_MW__Hydro,2015*)

Where the desired hydro installation MW is the annual amount of new hydro capacity required depending on the maximum hydro target. It is given by: (*Hydro_Capacity_to_be_Installed-Hydro_capacity__installed)/Capacity_adjustment_time,* where the Hydro Capacity to be installed is the hydro target.

The Solar and Thermal Investment Distribution

The equation for the fractional investment in solar PV after 2014 follows the logistic function given as:

$$Si = \frac{L}{1 + e^{\propto(Cs-Ct)}}$$

Where: *L* is equivalent to 1, and denotes the upper limit of Solar PV investment, which is assumed to be Annual electricity investment, less investment made in hydropower. *Cs:* is the cost of a megawatt unit of solar in Ghana cedis over time, *Ct:* is the cost of megawatt unit of a Thermal in Ghana cedis, ∝: is the unit multiplier and, *e:* is the exponential growth of the cost fraction over time.

The investment in thermal is therefore given by:

$$Ti = 1- \left(\frac{L}{1+e^{\propto(Cs-Ct)}}\right)$$

The equation above is consistent with the reasoning of Christensen, (1997) and Wilson & Grubler, (2011) that energy transitions follow the s-curve technology diffusion pattern. It is also consistent with the market share distribution between two competing technologies by Moxnes (1992). The investment in energy between solar and thermal is consistent with the theories of competing technologies. The Success-to-the-Successful (Braun, 2002) is operating between solar and thermal with the financial sector been the independent variable. The dynamics in the archetype below demonstrates the market share distribution between two investment alternatives.

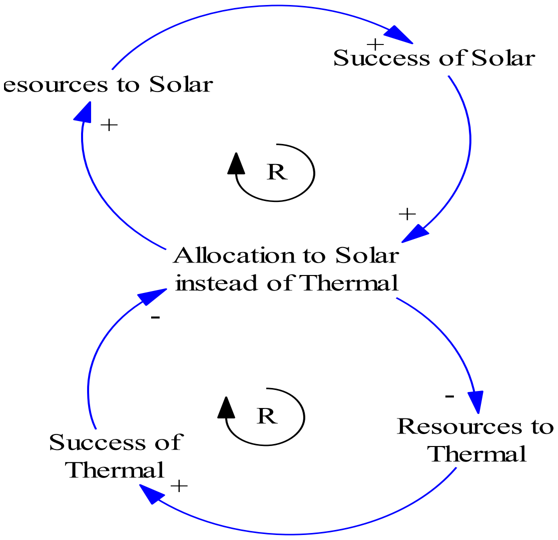


Figure 9: The archetype Success to the Successful

The investment in Ghana cedis of thermal is given by:

Investment_for__Thermal_and_solar-Solar_investment_in_cedis,

where investment for thermal and solar is the difference between total annual investment in cedis and the hydro investment in cedis.

The investment in Ghana cedis of solar is given by:

*IF Solar_Thermal_Policy_swicth =1 THEN (Investment_for__Thermal_and_solar*Fractional_Solar__Investment*Fractional_change)+(Investment_for__Thermal_and_solar*New_solar__investment_fraction) ELSE (Investment_for__Thermal_and_solar*Fractional_Solar__Investment)*

The 'IF THEN ELSE' function is necessary to formulate the change in solar investment, and also account for scenarios where solar policy is active and dormant.

3.1.5 The Causal Loops

The gap in demand and supply is an opportunity for potential investments in renewable energy. These investments could be focused on efficient and emerging technologies in renewable given shortcomings of fossil energy such as CO_2 emission. The feedback loops in the model are mainly balancing loops. The more the investment in electricity, the smaller the demand and supply gap becomes and lesser investment are consequently required. The investment decisions concerning the different power sources are a major part of this paper.

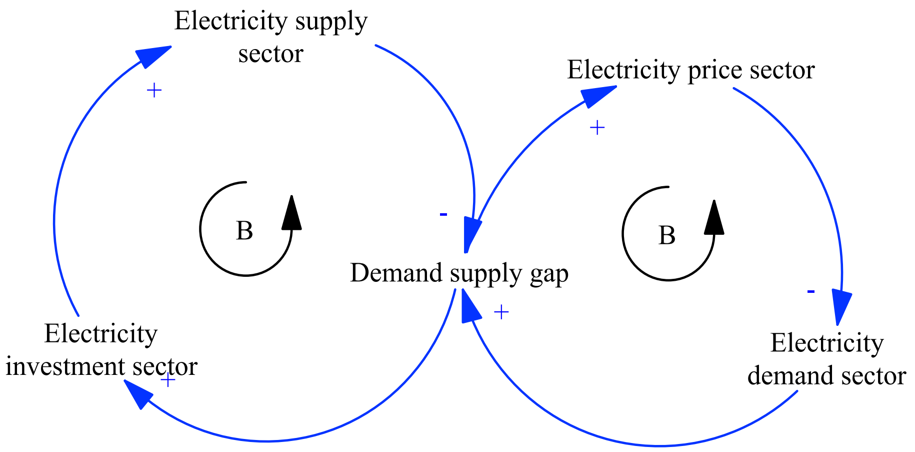


Figure 10: Main interactions within the model

There are about seven balancing loops and four reinforcing loops within the model. The major dynamics are a result of interactions between sectors. The causal loop diagram below presents a full overview of the dynamics in in the model. Parameters/variables highlighted indicate policy point for addressing the electricity concerns. The next chapter discusses in detail the result from the simulation and policy outcomes.

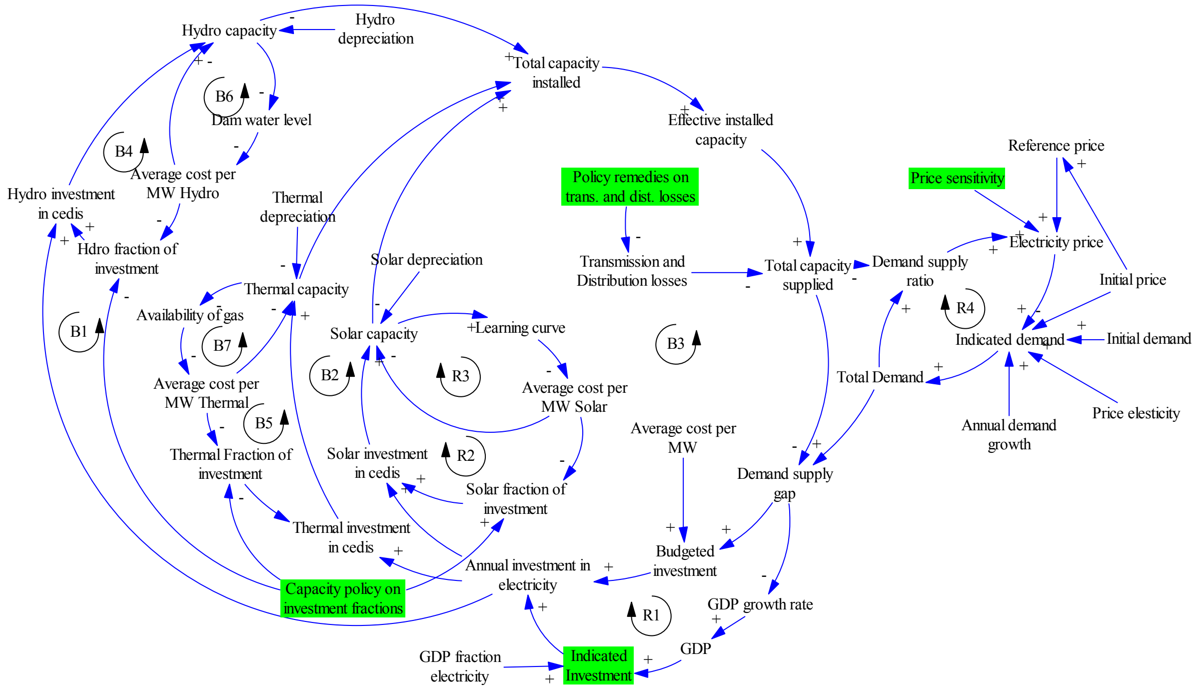


Figure 11: A Complete Causal loop diagram

3.1.6 The full model layout

The structure of the model consists mainly of four parts: the Electricity supply sector which represents the different power sources that makes up the total electricity potential in the country. The power supply is an important aspect of this study because it plays a vital role in the nature or trend of the demand and supply gap over time which is the goal of the study. The next sector in the model structure is the demand sector. This sector determines how much electricity is needed for the year. The demand is adjusted to the indicated demand which is a function of price, initial demand, and the demand growth rate over time. The demand sector is then influenced by the price sector. This sector represents the electricity price since 2000. A variation in price therefore affects the demand which in turn affects supply because the investment made in supply is adjusted to the demand and supply gap. The investment sector of the model entails the budgeted investment based on the demand and supply gap and the indicated investment which depends on the Gross Domestic Product (GDP) over time.

One thing that is essential in the model structure is that, due to various limiting factors, there is a distinction between installed capacity and effective capacity. The later refers to the fraction of the former that is fully operational. There is also a gap between the total effective capacity and the capacity that is consumed. The difference between these two is the power lost through transmission. There is a significant loss of power through distribution. This requires a policy action that updates the distribution systems to minimize post generation/transmission losses.

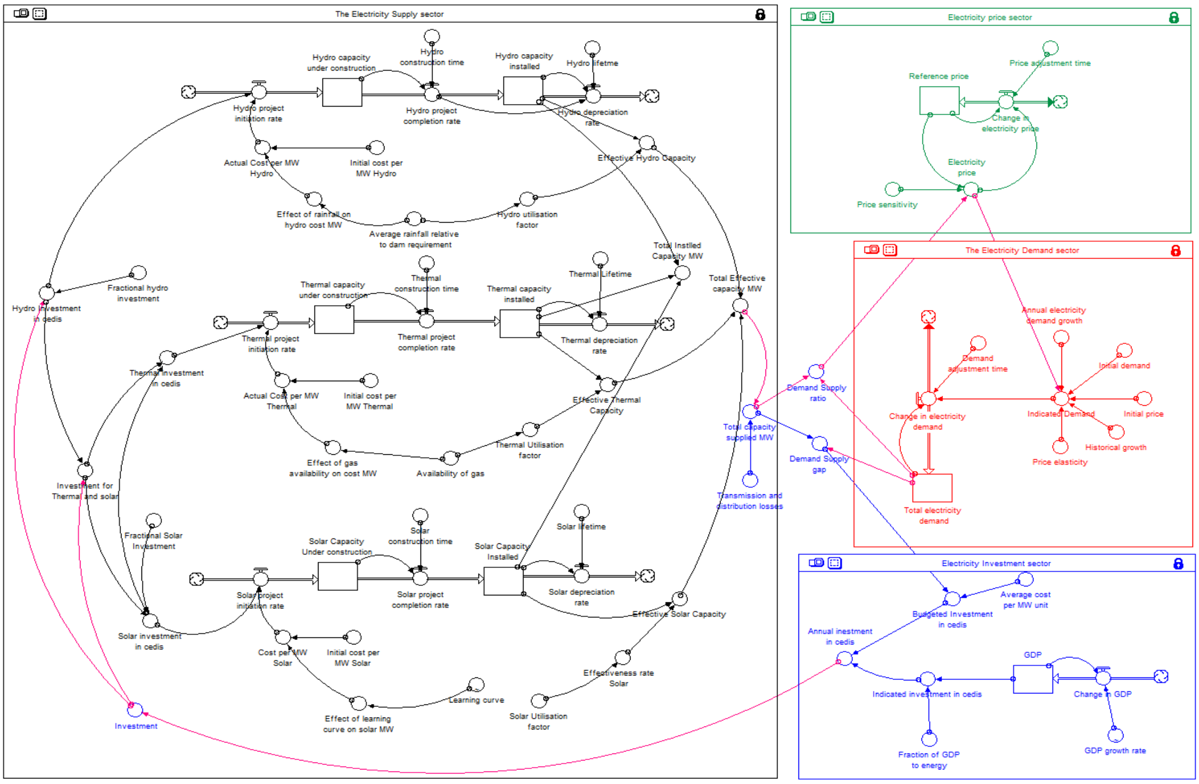


Figure 12: Stock and Flow diagram of the Model

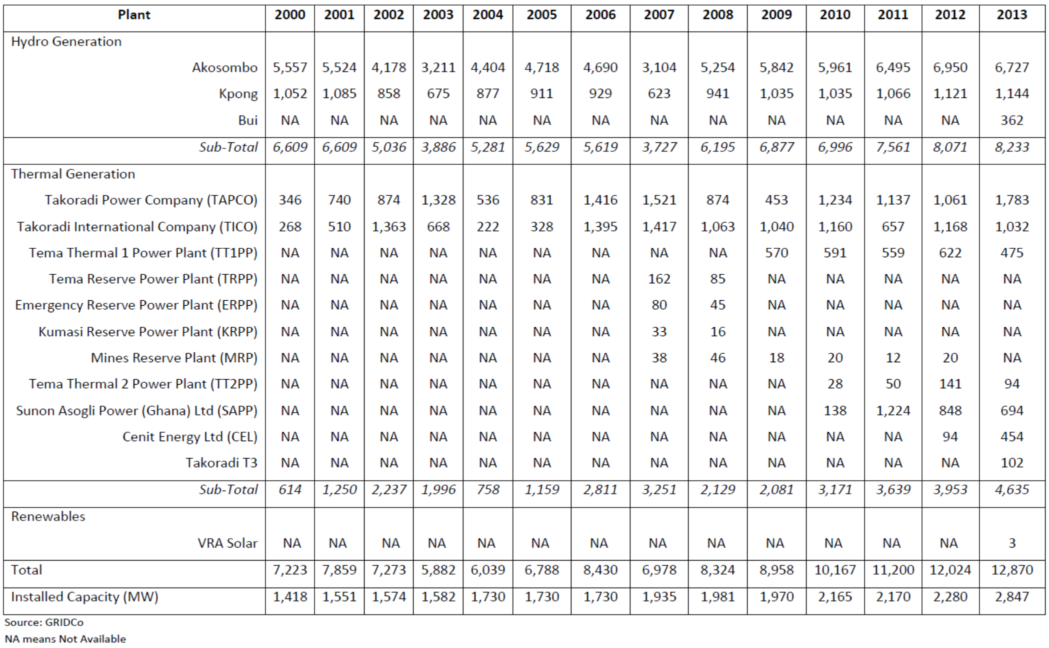
3.2 Model Analysis and Validation

Model validation is an essential part of system dynamics application. In order to ensure certainty that a given model developed represents a given underlying system, it needs to be rigorously examined before policies based on the model can be tested. There are difference forms of model validation: boundary-adequacy test, structure-verification test, parameter verification test, extreme-condition test, behaviour replication test, and dimensional-consistency test (Forrester and Senge, 1980). It is not necessary for all these tests to be conducted before a model can be deemed valid. According to Barlas (1996), a behavioral validity for a system dynamics model can be a sufficient to ensure that the model is valid.

The relevance of model validity is emphasized by subsequent studies in system dynamics. In order to strengthen the model validity, other calibrations and tests such as extreme condition test, unit consistency check (already conducted in the model), base run and reference behaviour comparison (demonstrated under figure 13 & 14), parameter sensitivity analysis, and structure-behaviour test (figure 15, 16 & 17) should be conducted (Sterman, 2001; Wheat & Saldarriaga, 2011).

The table shows the different power sources in the country and the total capacity of different plants under the power categories. The annual capacities from 2000 – 2013 are then compared to the simulation results.

Table 3: Plant Capacities



Plant	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Hydro Generation														
Akosombo	5,557	5,524	4,178	3,211	4,404	4,718	4,690	3,104	5,254	5,842	5,961	6,495	6,950	6,727
Kpong	1,052	1,085	858	675	877	911	929	623	941	1,035	1,035	1,066	1,121	1,144
Bui	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	362
Sub-Total	*6,609*	*6,609*	*5,036*	*3,886*	*5,281*	*5,629*	*5,619*	*3,727*	*6,195*	*6,877*	*6,996*	*7,561*	*8,071*	*8,233*
Thermal Generation														
Takoradi Power Company (TAPCO)	346	740	874	1,328	536	831	1,416	1,521	874	453	1,234	1,137	1,061	1,783
Takoradi International Company (TICO)	268	510	1,363	668	222	328	1,395	1,417	1,063	1,040	1,160	657	1,168	1,032
Tema Thermal 1 Power Plant (TT1PP)	NA	NA	NA	NA	NA	NA	NA	NA	NA	570	591	559	622	475
Tema Reserve Power Plant (TRPP)	NA	NA	NA	NA	NA	NA	NA	162	85	NA	NA	NA	NA	NA
Emergency Reserve Power Plant (ERPP)	NA	NA	NA	NA	NA	NA	NA	80	45	NA	NA	NA	NA	NA
Kumasi Reserve Power Plant (KRPP)	NA	NA	NA	NA	NA	NA	NA	33	16	NA	NA	NA	NA	NA
Mines Reserve Plant (MRP)	NA	NA	NA	NA	NA	NA	NA	38	46	18	20	12	20	NA
Tema Thermal 2 Power Plant (TT2PP)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	28	50	141	94
Sunon Asogli Power (Ghana) Ltd (SAPP)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	138	1,224	848	694
Cenit Energy Ltd (CEL)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	94	454
Takoradi T3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	102
Sub-Total	*614*	*1,250*	*2,237*	*1,996*	*758*	*1,159*	*2,811*	*3,251*	*2,129*	*2,081*	*3,171*	*3,639*	*3,953*	*4,635*
Renewables														
VRA Solar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
Total	7,223	7,859	7,273	5,882	6,039	6,788	8,430	6,978	8,324	8,958	10,167	11,200	12,024	12,870
Installed Capacity (MW)	1,418	1,551	1,574	1,582	1,730	1,730	1,730	1,935	1,981	1,970	2,165	2,170	2,280	2,847

Source: GRIDCo
NA means Not Available

In the figure below, the trend of the different power sources is show for the simulation period. In order to validate the model, the simulated results in compared to the historical behaviour in the table above. It is clear that, the simulate results in consistent with the reference data.

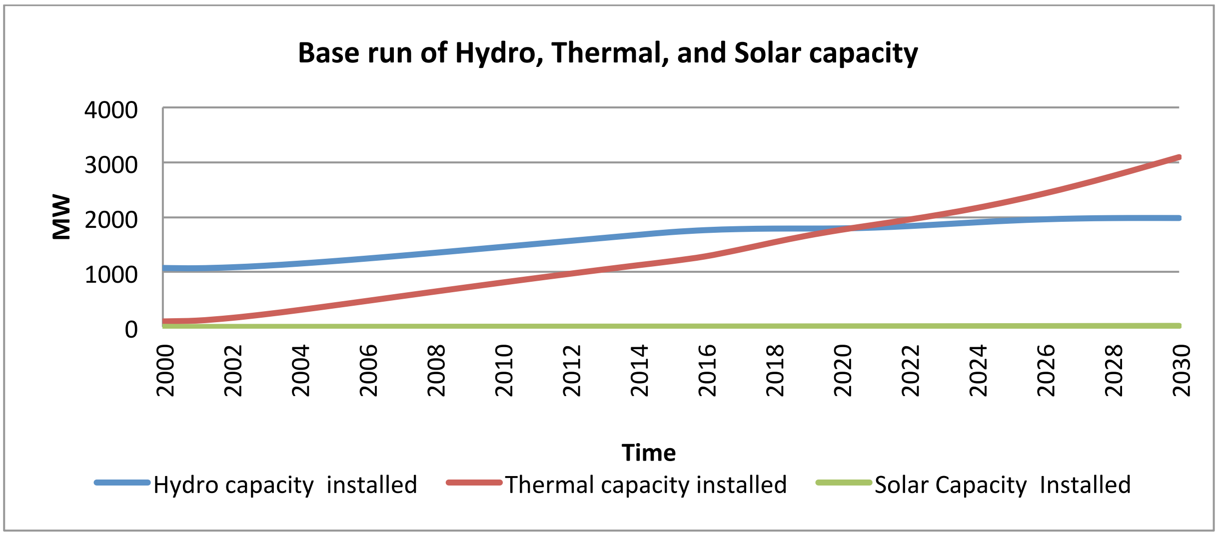


Figure 13: Simulated capacities of the different power sectors

Results of total capacity is not enough to affirm the validity of the model hence, other simulation results are evaluated. The demand and supply gap, the foundation of this study, is also juxtaposed with the reference data. As indicated in figure (14) below, the simulation results are consistent with the reference behaviour. The electricity demand and supply gap are similar to the historical data. Little disparity is observable. This is attributed to parameter assumptions such as average cost of MW per unit, which is taken as a constant figure in the model for lack of data. Other parameters such as the utilization factors were average values and not exact data over time. This does not adequately represent the real cost per MW. Other assumptions include the effect of learning curve, the cost of the different energy sources, the actual annual investment, among others.

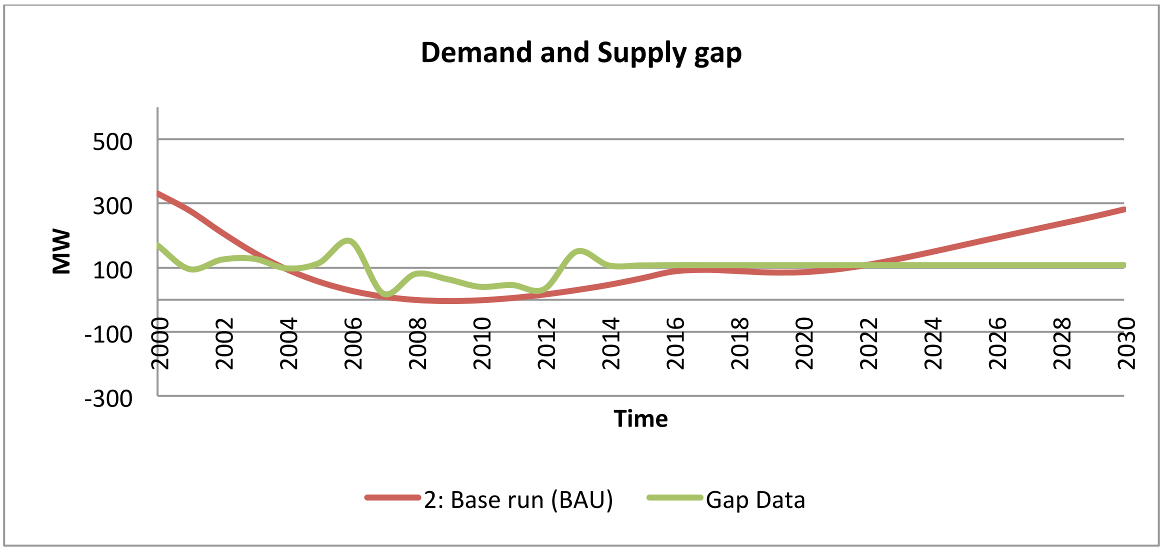


Figure 14: Demand and Supply Gap

3.2.1 Sensitivity Analysis

As part of validating the model, a parameter sensitivity test is also conducted to determine whether the mode responds as expected to parameter variations. The efficiency of sensitivity analysis depends on the extent to which variations in the model behaviour as a result of parameter changes can be deemed to have occurred due to such parameter changes. To ensure this, the model is initialized in equilibrium. Table 4 below shows some equilibrium values of the model and the values recorded under base run.

Table 4: An illustration of equilibrium values and base run at the end of 2014

Item	Hydro capacity installed	Thermal capacity installed	Solar capacity installed	Total demand	Average investment	Demand Supply gap	Total Effective Supply
Equilibrium value	1072	100	0	1161	550,000,000	331.56	829.44
Base run (2014)	1727.62	1197.05	2.03	2000.03	550,000,000	66.27	1938.76

Price is a central parameter any time demand and supply are involved. All things being equal, supply is expected to increase when price is high and decreases when price is low. Demand on the other hand is expected to increase when price is low and decreases when price is high. This can be seen in figure (15) below. As prices sensitivity is increased from zero (0) to two (2), demand falls from 7,000 MW to about 3,500 MW. This is expected based on the model construction/structure.

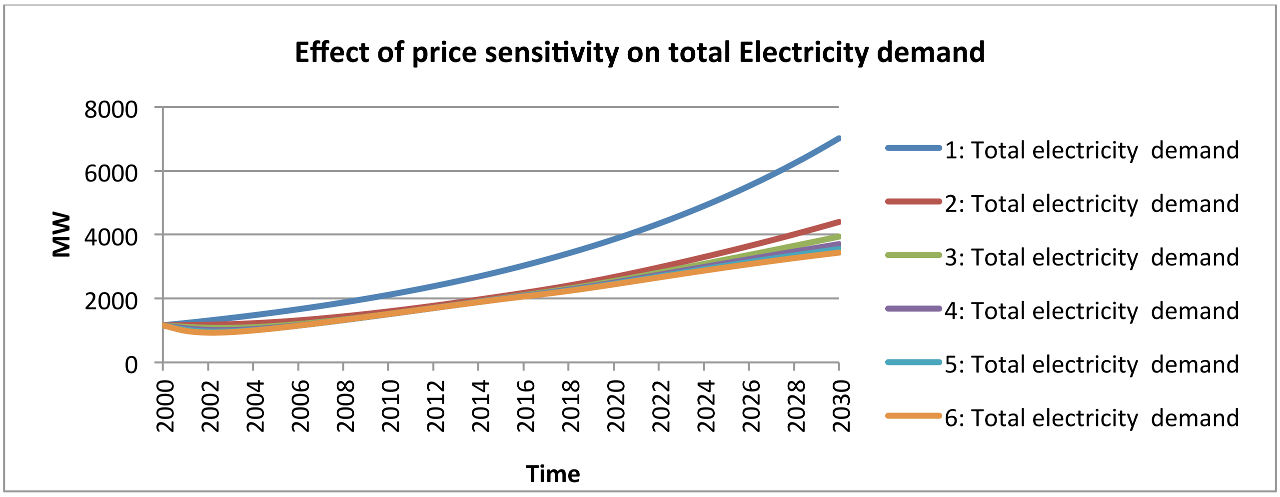


Figure 15: Effect of price sensitivity on Total Electricity Demand with varying price sensitivities (1: 0; 2: 0.4; 3: 0.8; 4: 1.2; 5: 1.6; & 6: 2.0)

The figure (16) below is the price sensitivity effect on supply. As price increases from zero (0) to two (2), the supply of electricity falls from about 5,900 MW to 3,300 MW. This seems illogical, however, it is the correct behaviour based on model structure. In the model, price has no direct influence on supply. This makes sense because, in Ghana, electricity sector is owned and regulated by the government. The absence of private sector participation eliminates possible competition and grants autonomy to the state. Price changes in electricity are therefore not market determined but rather fixed and reviewed by a state agency periodically. As price only affects the demand, an increase in price will lead to a fall in demand, which in turn leads to a decline in supply. The price increment does not set the incentive for an increase in supply as it would in the case of a free market operation.

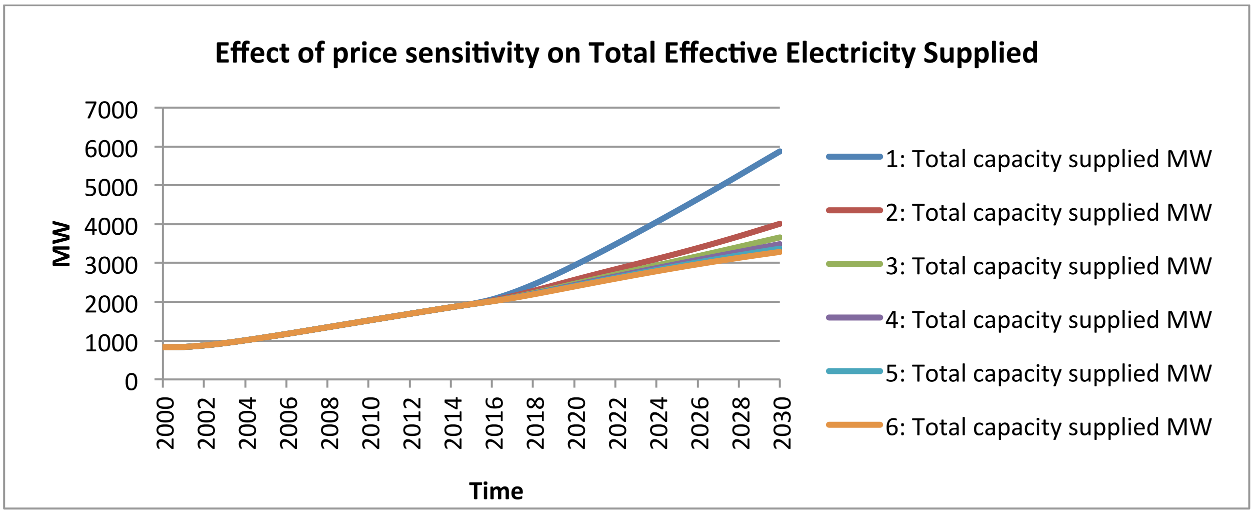


Figure 16: Effect of price sensitivity on Total Effective Electricity Demand with varying price sensitivities (1: 0; 2: 0.4; 3: 0.8; 4: 1.2; 5: 1.6; & 6: 2.0)

Indeed, investment in energy is affected by the price. Even though the electricity market is regulated, there is still a price effect on the investment decision. The investment needs created by price sensitivity in this model is counterintuitive. Usually, an increase in price would be an incentive to invest because there would be high returns, and a price reduction would prompt decline in investment. However, because the electricity sector is state-owned and the price is below indicated market price, an increase in price would result in a decrease in price.

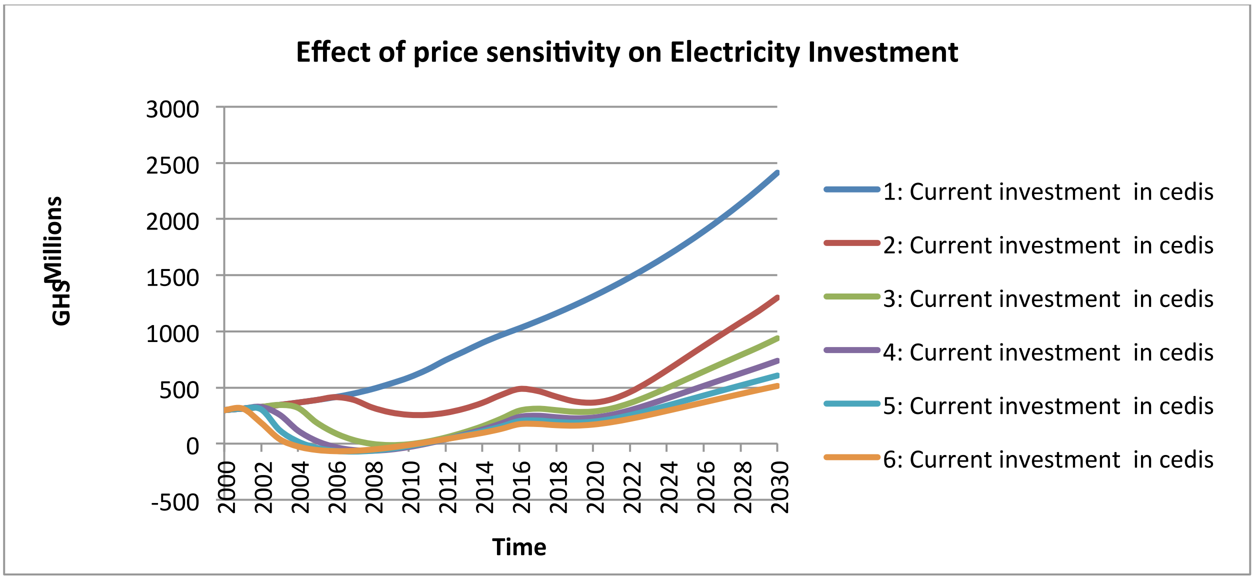


Figure 17: Effect of price sensitivity on Electricity Investment with varying price sensitivities (1: 0; 2: 0.4; 3: 0.8; 4: 1.2; 5: 1.6; & 6: 2.0)

The price increment would prompt demand to fall leading to a lower demand supply gap and indicating decline in the need for investment. This is depicted in figure 17 above. As price sensitivity is set at zero (0), investment increases at its highest because consumers can use electricity without paying. On the other hand, when price sensitivity increased to two (2), the need for investment is low because very few people are attracted to use electricity.

4.0 Results

The results from the simulation of the model developed specifically to analyze the energy sector in Ghana do not promise automatic solution. That is to say that, if this problem is not tackled now, it would not in any way become better by itself. The Business As Usual (BAU) scenario indicates that, the electricity problem in Ghana is only going to increase in the future. The results reveal five major issues in the electricity sector: There is the problem of low investment in electricity generation, significant amount of power lost, very low tariffs on electricity, underutilization of capacity, and fossil intensive investment. This calls for policy options and leverage points to alleviate this looming threat.

4.1.0 Base run

The base run presents the results from the simulation without any policy in place. It is supposed to replicate the business as usual scenario. As seen in the results presented, it is clear that, the simulated results do not exactly reproduce the reference mode. This is due to a number of disparities between actual values and estimated values. Figure 18 below shows the electricity gap between 2000 and 2013. It compares the demand and supply data to the simulated results and it is evident that, with the current trend of events, the problem would persist.

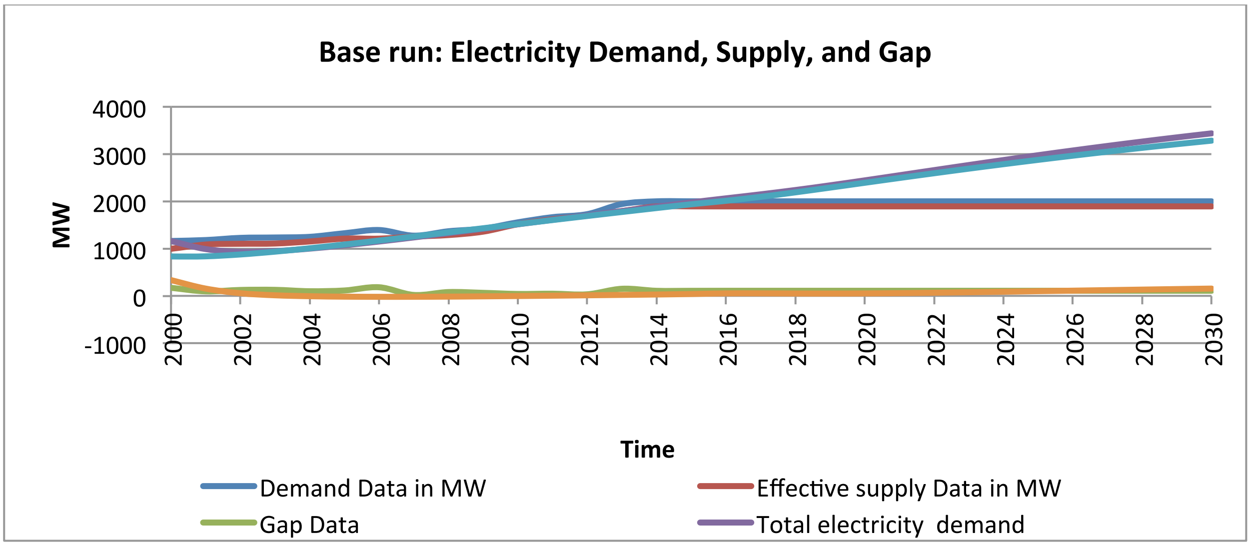


Figure 18: Electricity Demand, Supply, and Gap (Data and Simulation results)

The demand is below the effective supply, which is the effective supply capacity less transmission and distribution losses. Around 2008 and 2009 when some capacity of the Bui hydro project was commissioned, the electricity crises subverted momentarily.

4.1.2 Demand and Supply gap

The figure below shows the electricity gap since 2000. Demand exceeding supply presents power deficit situation in Ghana. As demonstrated in figure 19 below, the demand of electricity is above that of the effective supply creating a gap over time.

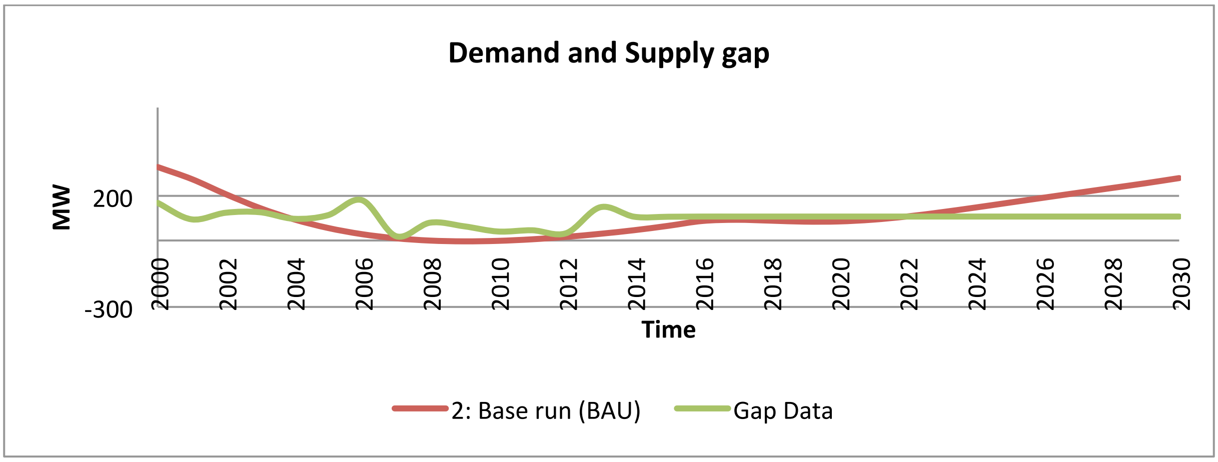


Figure 19: Demand and Supply Gap

The addition of some megawatt units from some thermal plants reduced the crises in the middle of the last decade. In 2007, the Akosombo hydroelectric power station suffered its first severe water crises resulting in nationwide load-shedding. This prompted the construction of more thermal plants. Since the first crises, the dam has never been fully functioning as the thermal plants that were supposed to share the burden are operating below capacity. In 2011, when a ship anchor destroyed the gas pipeline that provide gas to the thermal plants all the way from Nigeria, the power crises became intense. The simulation results in figure 19 depict the sudden rise of electricity gap in 2012. Intermediary solutions have merely scratched the surface of the problem.

4.1.3 Total Installed, Effective, and Supplied Capacities in MW

One of the main issues of concern that the model has revealed is the fact that, there is a significant difference between the total capacity of power installed, what is effectively generated, and the actual megawatts of power distributed to consumers (figure 20). Out of the total capacity installed, only a fraction of this is effective. This is due to different reasons that affect the functionality of the different power plants/sources. In the case of hydro, the total capacity is that is effective is only 90% of the capacity installed because the lack of rainfall during the dry season worsens the already under-producing hydroelectric turbines. With thermal, the effective capacity is merely about 70% of total installed capacity, on average. This disparity is mainly due to the unavailability of gas to operate the plants. Relying on gas from Nigeria is a rather worrying dependency relationship. In the case of solar, issues of underutilizations are often related to the darkness at night. The location of Ghana has made it ideal for solar power all year round, even during the rainy season.

The sum of these effective production capacities is still not what is distributed and accounted for at the downstream supply chain. As the simulation in figure 20 below shows, the supplied capacity is less than the effective capacity.

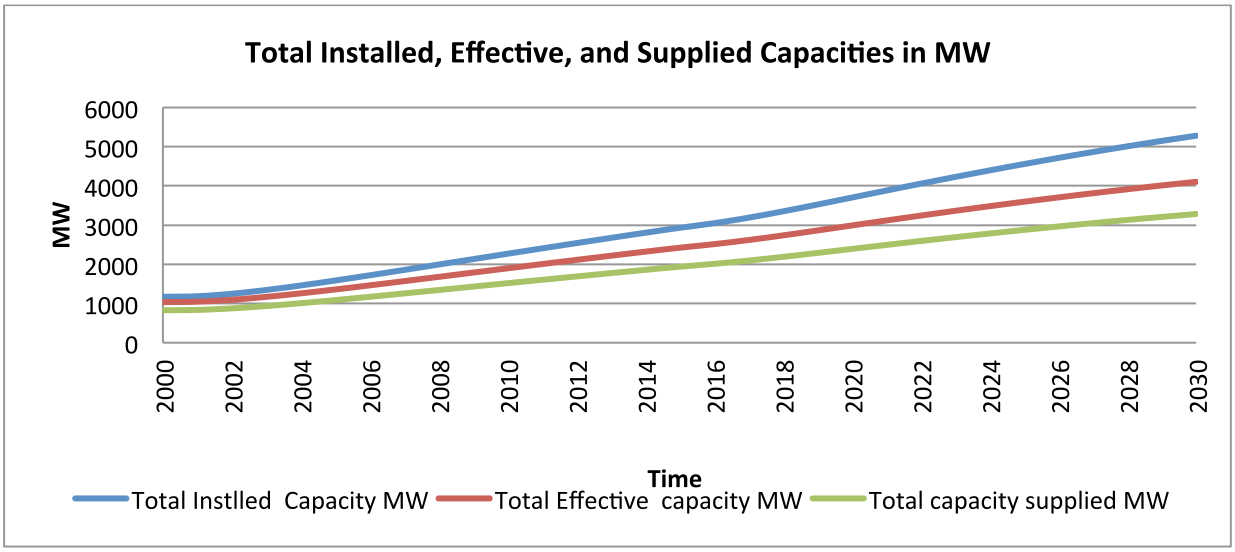


Figure 20: Total Installed, Effective, and Supplied Capacities in MW

This is because, in Ghana, there is significant amount of power lost from generation to distribution. About 5% on average, of the power generated is lost through transmission and about 20% of the power is lost through distribution. This is a major issue that needs keen attention.

4.1.4 Electricity Pricing

Electricity pricing is another issue that is very important in the overall discussion of the energy situation in Ghana. In Ghana, the prices of electricity are fixed over time and reviewed by a commission that also regulates water tariffs. The Public Utilities Regulatory Commission is responsible for reviewing electricity prices in Ghana. As regards, the tariffs on electricity are very low compared to market prices.

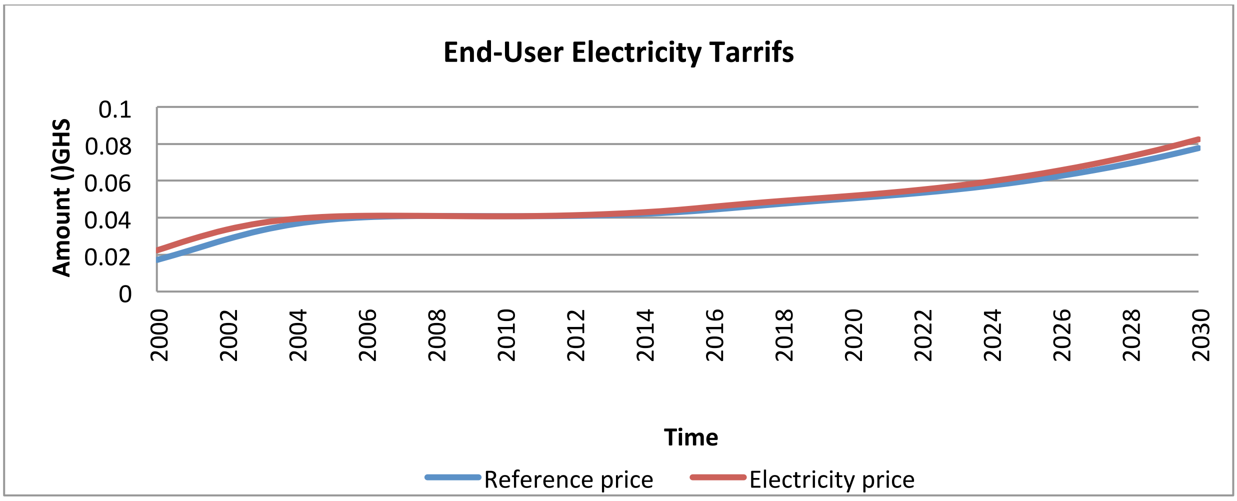


Figure 21: Annual Electricity tariffs

Electricity in Ghana is also heavily subsidized by the state. The end-user price is therefore very low, an incentive for high electricity consumption. Figure 21 above shows the electricity price in Ghana. It is apparent in the simulation, that electricity price increases slowly. This price is even lower than many developed/industrialized nations that have a lower per unit cost of production.

The figure below shows how a variation in the price sensitivity could affect the demand and supply gap. When price sensitivity is very low, the gap would increase because electricity is cheaper since it does not respond to market mechanisms.

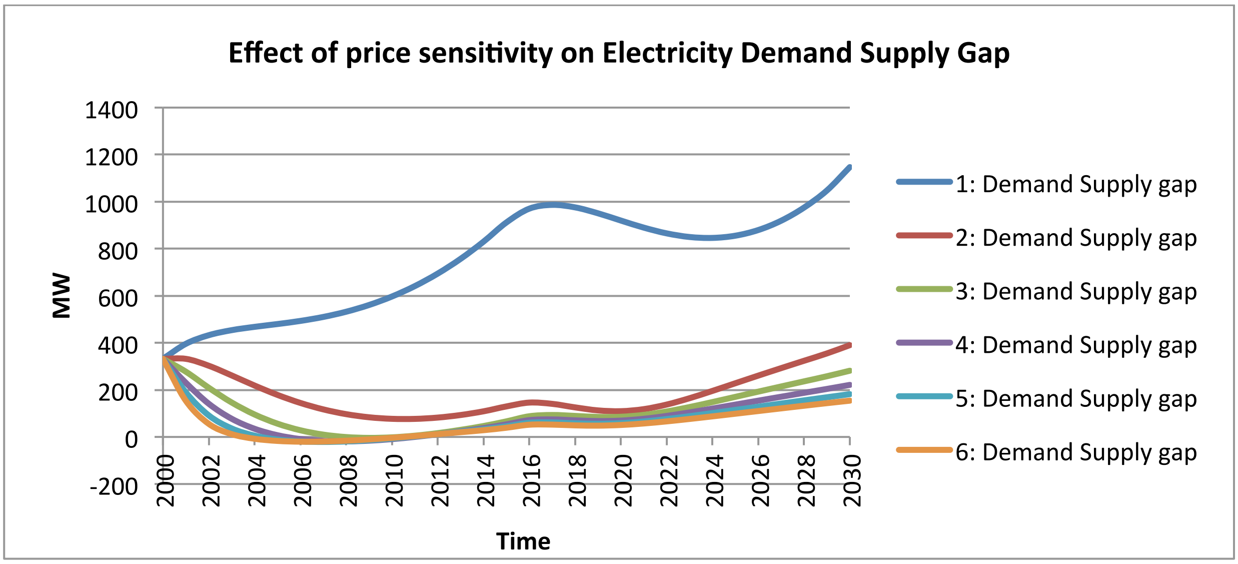


Figure 22: Effect of price sensitivity on demand supply gap with varying price sensitivities (1: 0; 2: 0.4; 3: 0.8; 4: 1.2; 5: 1.6; & 6: 2.0)

On the other hand, when the price is very sensitive, the demand for electricity declines leading to a lower gap as depicted in figure 22 above. This presents another policy option for the government to alleviate this growing concern.

4.1.5 Electricity Demand and Indicated Demand

Demand is derived from the indicated demand. Indicated demand is higher than demand throughout the simulation period. Figure 17 represents the development of the demand and indicated demand over time. The price effect is shown in the indicated demand. A lower demand supply ratio below 1 would suggest that, electricity price is lower than the reference price. In other words, when the reference price of electricity is higher than the actual price, it would prompt the indicated demand to fall below the actual demand, contrary to the simulation in figure 23 below. The need constant rising trend of demand is indicative that, price is indeed very low hence, encourages more demand.

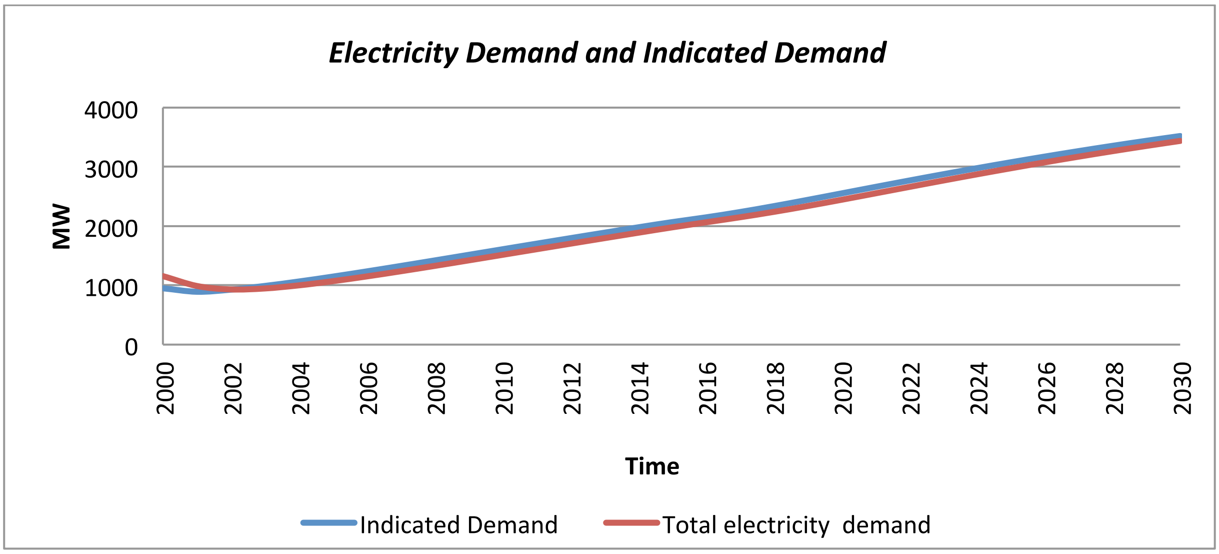


Figure 23: Electricity Demand and Indicated Demand

4.2.0 Policy Analysis

Policy formulation is an essential aspect of decision-making. A system Dynamics model that contains within it a policy structure also embeds in itself some implementation assumptions (Wheat, 2010). Identifying the issues causing undesirable dynamics in a system is only one part of problem solving. After 'troubleshooting' the next step is to identify ways of overcoming rectifying the issues. This study proceeds to evaluate the policy options considered in the model. There are five main policy related issues covered in the model. They include the investment alternatives, the transmission and distribution losses, the capacity issue, and the pricing system in the electricity sector.

4.2.1 The Investment policy

Governments' attempt to bridge the power deficit in Ghana has been in a goal-seeking pattern. Power decisions are made with the demand supply gap as the target. Unfortunately, the gap is a moving goal that changes from year to year. Whilst plans are advanced to bridging the gap observed in the previous year, very little consideration is given to the annual demand increment. The growth in industry, extension of power gird to rural communities, and potential seasonal and unforeseen hindrances are not given enough thought. The results from the simulation indicate that, an increased investment beyond the demand and supply gap is required to overcome this incessant problem.

The simulation below shows two investment pathways. The budgeted investment, which is the investment government made based on demand and supply gap is insufficient to solve the crises. This low investment is one of the reasons why the gap persists.

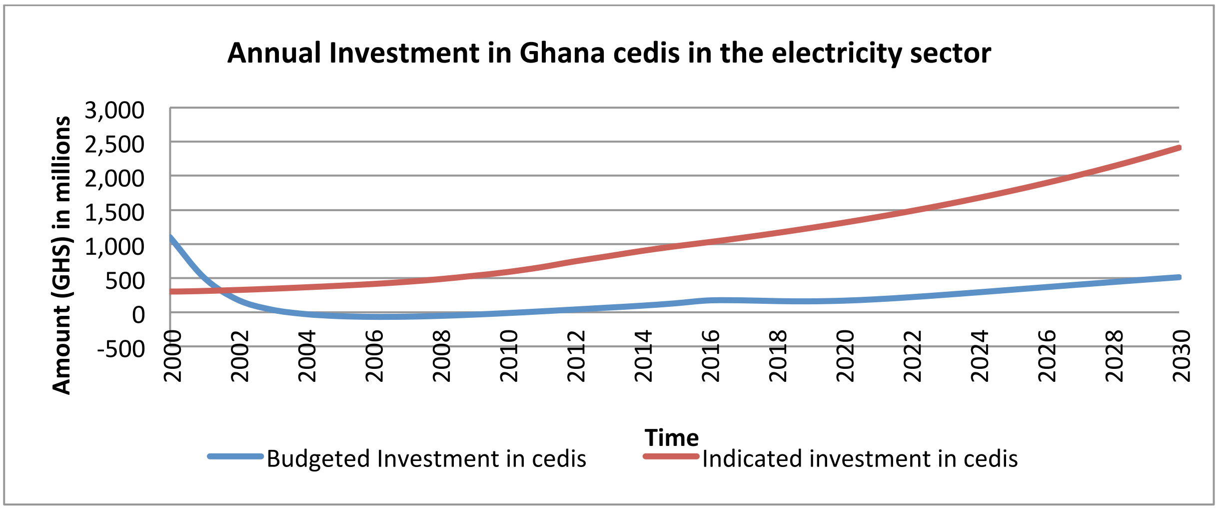


Figure 24: Annual Investment in Ghana cedis in the electricity sector

If the government keep benchmarking investment with demand and supply gap would be as indicated in the base run in figure 25 below. On the other hand, the indicated investment in figure 24 seem appropriate scenario to overcoming the electricity crises. This investment is derived from the GDP trend. Indeed, as the Energy-led-Growth-led-Energy scholars (Masih & Masih, 1997; Fatai et al, 2004; Ghali and El-Sakka, 2004; Akinlo, 2008) hypothesized, there seem to be causality between economic growth and energy consumption. It is estimated that, electricity investment in Ghana needs to be equivalent to about 1.5% of GDP. Investing at this rare will result in an elimination of the gap as indicated in figure 25 below.

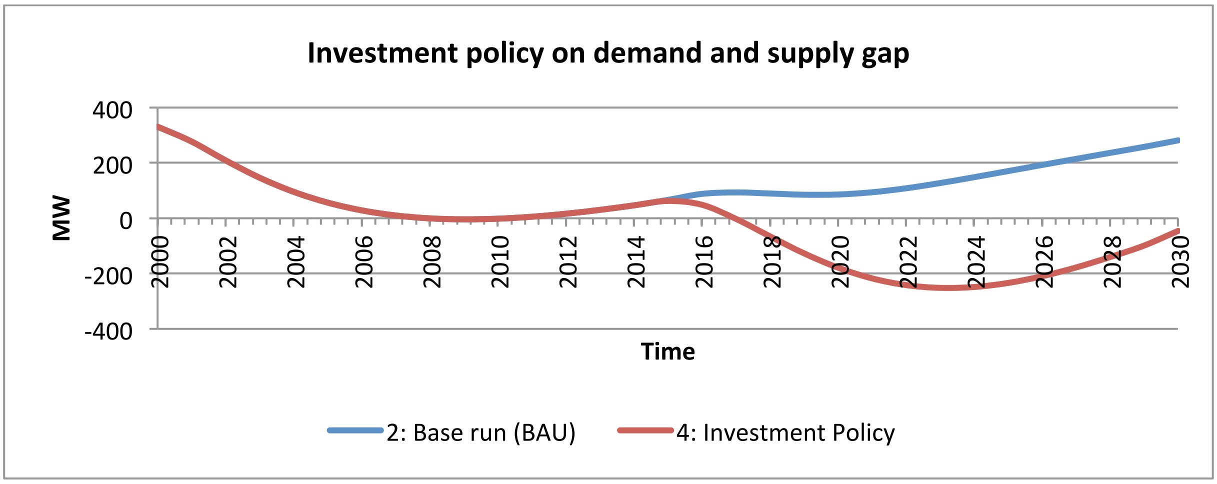


Figure 25: Investment policy on demand and supply gap

The investment policy is therefore an effective policy for solving the electricity crises. This should be a wakeup call for the government to collaborate with the private sector to boost investment. A good incentive for private sector participants will be a free and fair market system where the price of electricity is market regulated and not solely determined by the Public Utilities Regulatory Commission.

4.2.2 The Capacity Policy

Hydro limit: The capacities policy does not appear to be viable unless it is paired with some other policy options. The policy however is worth considering because; the hydro potential in Ghana is highly limited. Although hydro constitutes a greater amount of power sources for electricity, there are not that many viable hydro sites that could be developed in the future. This policy sets the maximum hydro capacity at 2000 MW. This implies that, only about 400 MW of hydro can be developed in the future. The policy sets a scenario where by all these potential sites are developed by the end of the simulation period.

Solar/Thermal capacity proportions: This capacity policy evaluates the extent a deliberate focus on varying the different power capacities over time with the available investment might resolve the gap. The Solar/Thermal policy is a priority due to varying returns in the future. Solar is expected to record increasing returns over time as the unit cost decline due to the learning effect. The Thermal unit cost on the other hand is expected to increase as gas supply is exposed to unstable political environment. Again, solar technologies are expected to advance in the future and reduce the unit cost making competitively favorable. The policy on solar and Thermal is therefore activated with the hydro capacity policy which simulates the maximum potential hydro capacity over time.

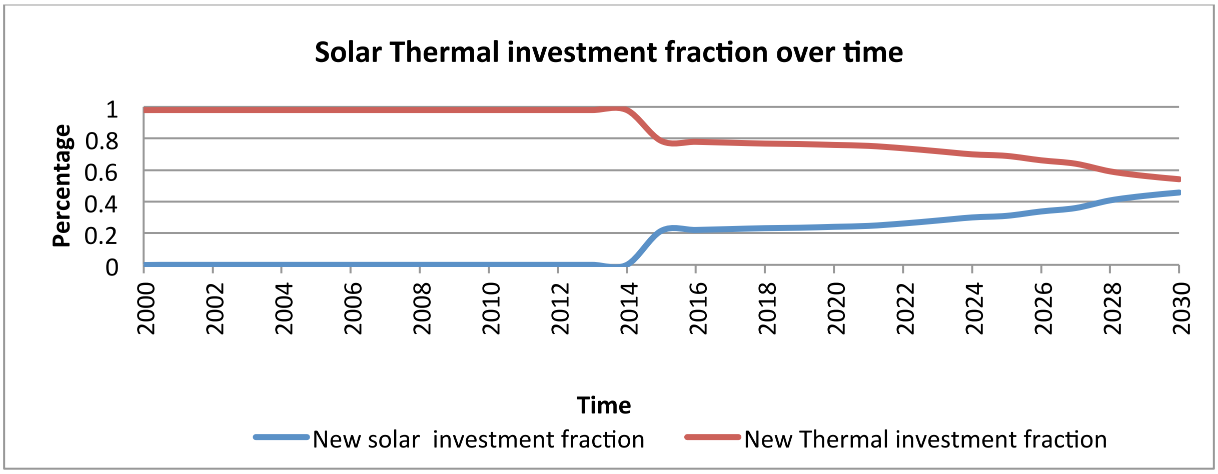


Figure 26: Solar/thermal market share over time

The figure (26) above indicates the market share of solar and thermal over the simulation period. As the learning curve effect reduces the cost per unit, solar becomes more favorable and attract investment. Thermal on the other hand gradually loses market share and become less attractive. The transition from solar to thermal follows the s-curve technology diffusion pattern (Christensen, 1997; Wilson & Grubler, 2011). At the end of the simulation period however, thermal still has the highest market share. Energy transition takes time. Technology adaptation that involves high setup capital takes off slowly. In the long-run however, solar will overtake thermal as a cheaper electricity source.

Figure 27 below illustrates the gap if only the capacity policy is activated. This means that, hydro investment reaches its maximum of 2000 MW in 2030. Additional capacity from now to the end of the simulation period is 400 MW. A fraction of this is invested annually.

Remaining funds after hydro is allotted to solar and thermal based on the fraction of market share. At the end of the simulation period, the policy outcome is equivalent to the base run but with a rather larger gap between policy start to end time. The capacity policy, though necessary needs to be combined with other policy options to realized positive outcome and secure a sustainable energy future in Ghana.

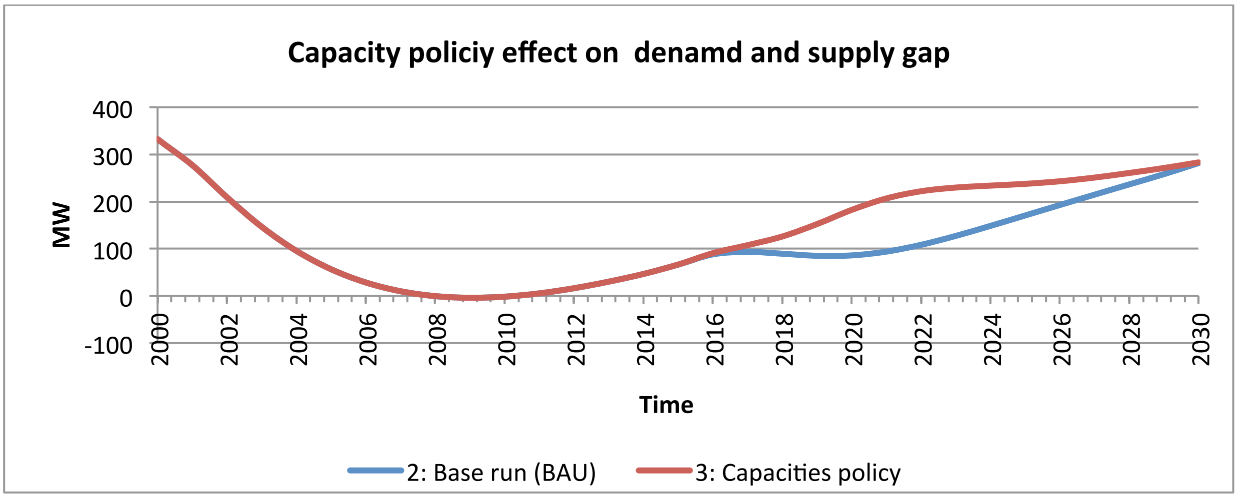


Figure 27: Capacity policy effect on demand and supply gap

4.2.3 Transmission and Distribution losses

The transmission and distribution losses are a major contributor to the low supply of electricity in Ghana. The model proposes a policy that reduces the transmission and distribution losses by a fraction. This policy aspect uses Sabatier and Mazmanian's, (1980) idea of parameter testing using an estimate of the parameter value. The historical data on transmission and distribution losses is presented in *appendix 1*. The transmission policy assumes a reduction of the losses by 50% to see how that affects the demand and supply gap.
Figure 28 below shows how a 50% reduction in transmission and distribution losses could reduce the demand supply gap significantly.

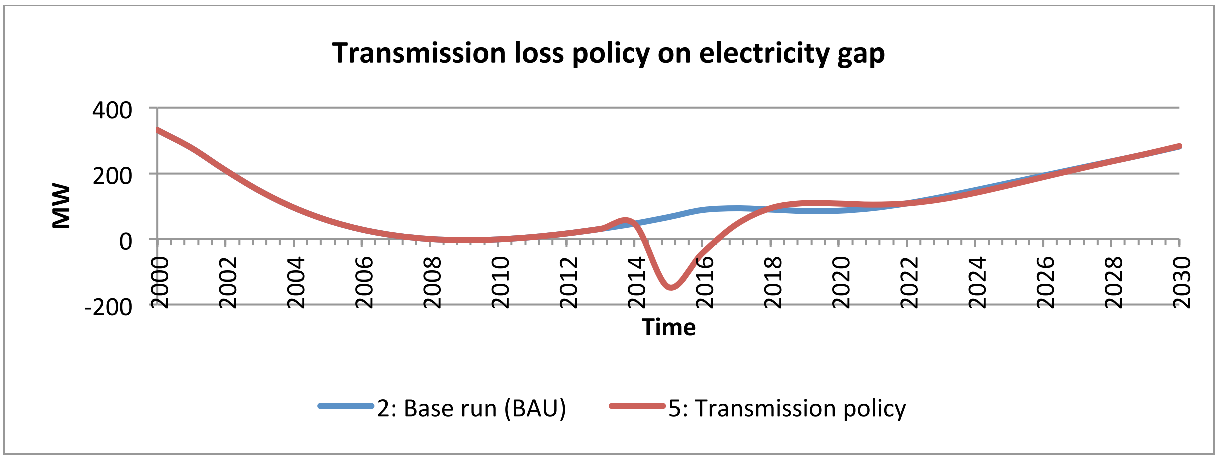


Figure 28: Transmission and Distribution losses

Government should therefore redirect some of the investment made in construction of new power plants to improving the distribution system and reduce the power losses. Without proper attention to the power, the need for construction of new power stations will continually increase. Proper maintenance on existing grid and improvement in the metering system to eliminate power theft would hugely improve the power supply in Ghana.

4.2.4 Combined policies effect

The results in figure 29 below show the gap development over time if all the policies are activated. This among other reasons makes solar the competitively viable alternative for electricity needs. At the end of the simulation period, it is estimated that the gap will begin to emerge again with all policies activated. This is because; the weight of the ineffective policies dominates in the long-run. The best policy option or combination of options should therefore be settled on. This is discussed further under policy comparisons below.

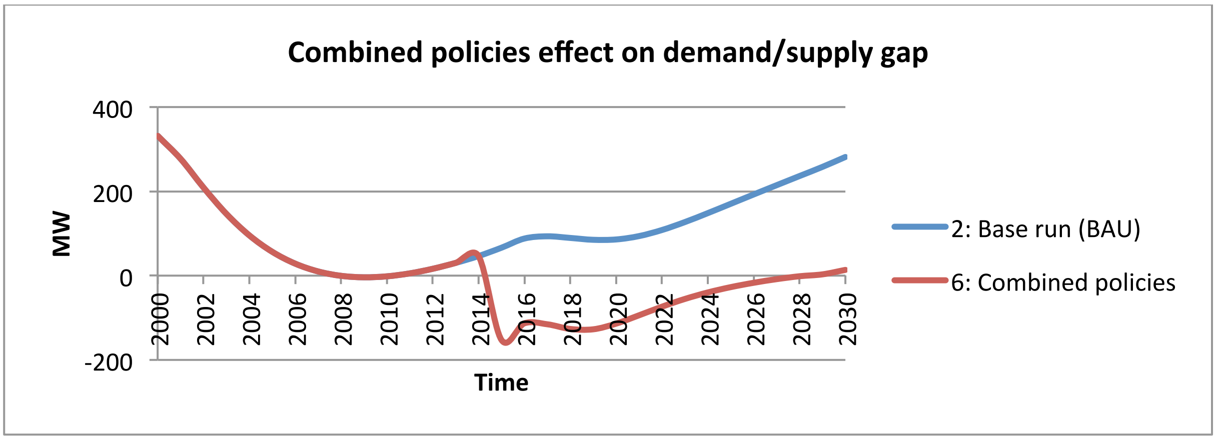


Figure 29: Combined policies effect on demand/supply gap

4.2.4 Policy combinations and Comparisons

The policy combination presents the scenario where all policies in the model are activated. The results are then juxtaposed with other policy options to determine whether a single policy option presents better outcome.

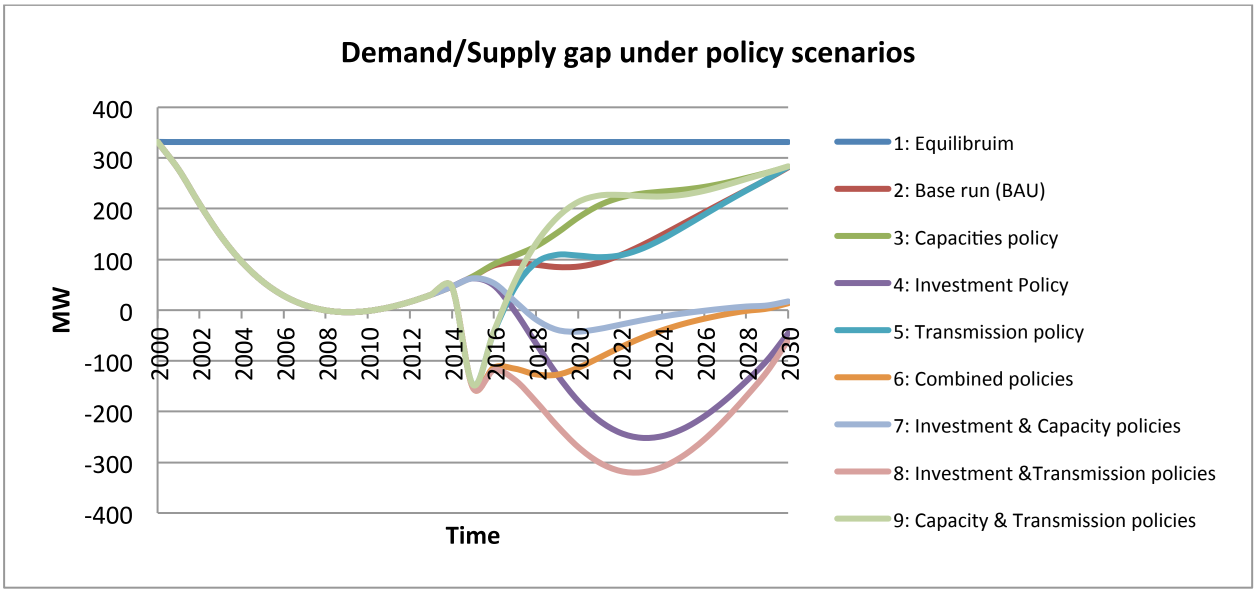


Figure 30: Different policy combinations

The investment policy seems to be the best approach to the current electricity shortage in Ghana. As depicted in figure 30, the investment policy is the one that has the highest impact on the demand and supply gap. This policy is therefore recommended to policy-makers. On the other hand, the capacities policy does not in itself solve the crises in the long-term. Policies that do not contain investment are not effective in the log-run.

The capacities policy is ineffective because, the hydro capacity is limited and thermal and solar are both still more expensive compared to hydro at the end of the simulation. All the policy options that include investment present better results than all other policies. This reiterates call for more investment to be made in the electricity sector. Whether this investment comes in the form of constructing new power stations or improving existing one, the reality that investment is ideal and necessary is inevitable.

4.2.5 Total installed capacities with all policies activated

The figure below shows the total capacities recorded at the end of the simulation period if all policies contained in the model are activated. The high capacity reaches its peak of 2000 MW and the effect of depreciation is setting in. The limited nature of hydro resources makes it least ideal a major policy option notwithstanding the relative cost advantage of hydro to other energy sources.

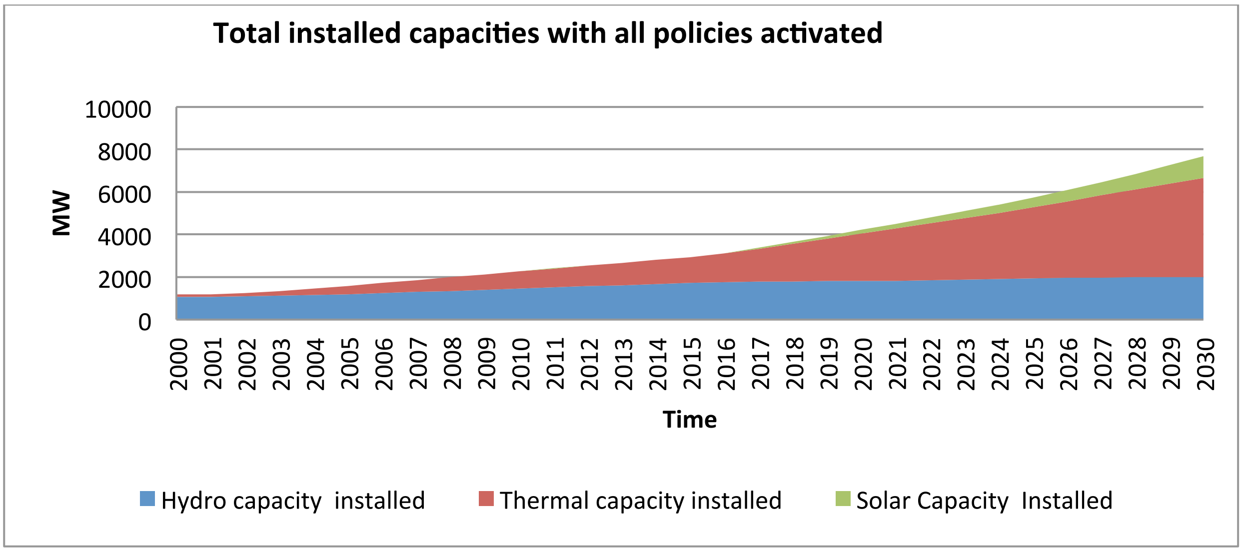


Figure 31: Total Hydro, Thermal, and Solar PV Capacities MW

The figure (31) presented above indicates a growing trend of the thermal capacity in the country. This is partly due to the gradual liberalization in the electricity sector to encourage private sector participation. Even though thermal seem affordable now, there are some pertinent challenges associated with it. For instance, in 2012, a ship anchor cut the West African Gas Pipeline which transports gas from Nigeria to Ghana. This result in near zero production from the thermal plants creating a severe electricity crises, the remnants of which are still experienced today though repair work on the pipeline is almost complete.

Solar is increasing more rapidly because the unit cost MW of solar is declining. This is as a result of the learning curve effect. Even though the cost of solar at the end of the simulation period is still slightly higher than that of thermal, there is high potential for further decline as it gains more market share. The simulation period is not long enough to accrue a quantitative net benefit. Qualitatively, investment in solar is future-oriented, reliable, and sustainable compared to thermal.

Net present value

Given the short time period of the simulation, policy cost evaluation suggests that there is no positive net present value. The solar cost for instance is still slightly above the thermal cost. Thought the pattern suggest a positive and higher return on solar after the simulation period, it is hard to accrue net present value in the short-term since investment in solar PV is a capital intensive undertaking and returns are not readily realized.

5.0 Discussion of Results

Nearly all the electricity provided in Ghana is provided by the government. In recent times, there have been discussions of market liberalization to encourage private sector participation in the energy sector. Active participation of the private sector will lessen the burden or responsibility on government to independently provide all the energy needs in the country. Policies should be instituted and strategies designed to relax the entry barriers that detract potential independent investors. The regulations should be relaxed to accord private entities a convenient platform to operate in the sector.

Simulation suggests that, even though there are some major issues with the power generation, policy makers give little attention to the contributions of demand side to the overall problem. There is little consideration on the magnitude of the effect of changes electricity demand poses to the electricity problem in the country as postulated by Gyamfi (2007) and Adom et al. (2012). This reemphasizes the findings of Ackah and Adu (2014) that determining the factors driving the electricity demand can inform policy makers to institute the appropriate policies manage and bridge the power deficit in Ghana.

Electricity supply should be a key priority to stakeholders. It is central to economic development and individual well-being. Ghana's electricity data indicate a rather narrow energy mix at the national level. Little attention has been given to energy sources that are abundant and not heavily constraint by seasonal/perennial factors (such as rainfall) which are major causes of the current energy predicament. Emerging technologies far more efficient, effective, and environmentally friendly are far less explored in Ghana. Renewable energy sources such as solar should be considered. The current rampant plant shutdowns as a result of limited gas supply as made thermal a less ideal choice for sustainable energy future in Ghana. The result from the simulation of the solar and thermal market share in future based on current cost values indicates that, solar will eventually emerge as a cheaper source of electricity to thermal.

The results from the investment analysis suggest that, the target annual investment should not be the demand and supply gap as this will always result in the government responding late to investment needs and also consistently recording a gap between demand and supply of electricity. The indicated investment computed based on the GDP growth over the simulation period is the best investment alternative for future electricity sufficiency.

It is estimated that, approximately 22% of the electricity generated in the country cannot be accounted for. This is lost through transmission and distribution. There are numerous grid cables that are absolute and sub-standard. As a result, they are inefficient in transmitting and distributing the total generated power to final consumers. Problems of illegal connections, billing and revenue collection, and poor metering system account for commercial losses in downstream process. The results from the study suggest that, a critical policy focus on reducing the transmission and distribution losses could improve the electricity supply enormously.

The current regulatory mechanism in the electricity market is ineffective and partly responsible for the high energy consumption in Ghana. The electricity price is not determined by the demand and supply pressures. Electricity in Ghana is also highly subsidized compared to many developed economies. As regards, there is very little effect on price even when demand far exceeds supply. The Public Utilities Regulatory Commission which is responsible for setting electricity tariffs also adjusts price in significantly large time step (one year). This creates a slow reaction of price to demand and supply. It also serves as a disincentive to private entities that have the desire to invest in the energy sector. Preliminary results on pricing policy option suggest that, a market determined price is much more beneficial than the ‘fixed’ pricing system currently in use. In this model, the policy returns are a bit complicated to compute. This is especially the case since most of the policies are qualitative in nature. For instance, improving management efficiency to reduce distribution loss would require some of incentives or repression upon failure. These incentives or deterrents are not easily measurable in monetary terms.

6.0 Conclusions and recommendations

The electricity problem in Ghana seem to be emanating from low investment, especially in renewable energy, excessive transmission and distribution losses, and underutilization of capacity due to seasonality factors and gas supply inconsistencies. This places emphasis on the need to investment in renewable energy. Indeed, the set-up capital is high, the cost ratio to fossil is currently high, but the long-term benefit must not be overlooked for short-term political income that leaves the problem far worse every year. It is high time the government liberalize the electricity market, encourage private sector participation, promote a free market system, and clamp-down on illegal grid connections that accounts for nearly a quarter of total electricity generated.

A market-based price reduces energy 'wastage', reduces supply gap, and also reduces the subsidy required on electricity. Reduction in subsidy could lead to more funds for expansion capacity. The government should therefore adopt a free/market based mechanism where prices instantly respond to demand and supply capacities. One advantage of this is that, there is an incentive to conserve energy as it is rewarding to reduce consumption.

The regulatory agencies need to be more proactive in discharging their duties. The Energy Commission needs to set out clear directives to Independent Power Producers who procure license to produce electricity. Licenses should only be issued to reliable private sector entities capable of producing the amount of electricity for which such license has been issued. A clear timeline should also be set for such entities to attain certain production level. This reduces the repercussions government endure in response to address perennial electricity supply gap.

In existing electricity grids, measures can be taken to reduce technical energy losses. The losses are relatively higher when there is low voltage. Options include upgrading the voltage of a transmission and distribution system, and replacing existing transformers with more efficient ones. Electricity conservation and efficiency is very low in Ghana. Though this can largely be attributed to the nature of household appliances (old and sub-standard) and "stolen power", the high subsidy on electricity resulting in prices far lower than some highly developed countries is a huge incentive for excessive usage.

There is the need for further studies in the Ghanaian energy sector that takes into consideration complete historical data of utilization over time and not average values as contained in this study, to ensure a much concrete prediction of the electricity scenario in the future. Future research should also find actual data on investment in the different power sectors. This could yield more resilient results than the calculations in this study which computed the annual investment by calculating backwards with the overall capacity installed over the period and evenly spreading that over the historical period. The actual cost of a MW unit of solar and thermal should be carefully computed to ensure a better judgement of market share distribution/development over time.

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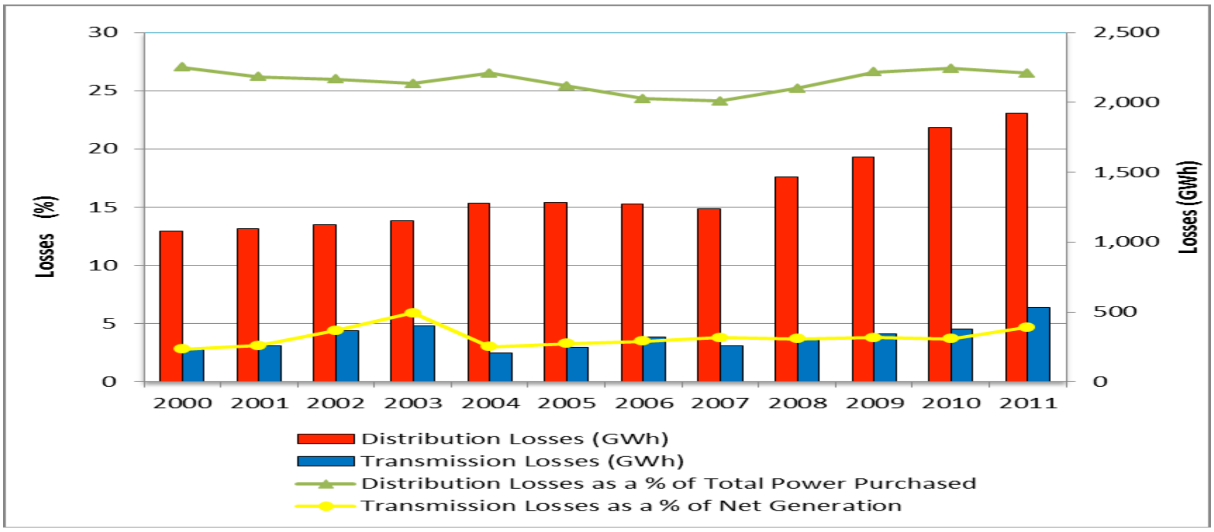
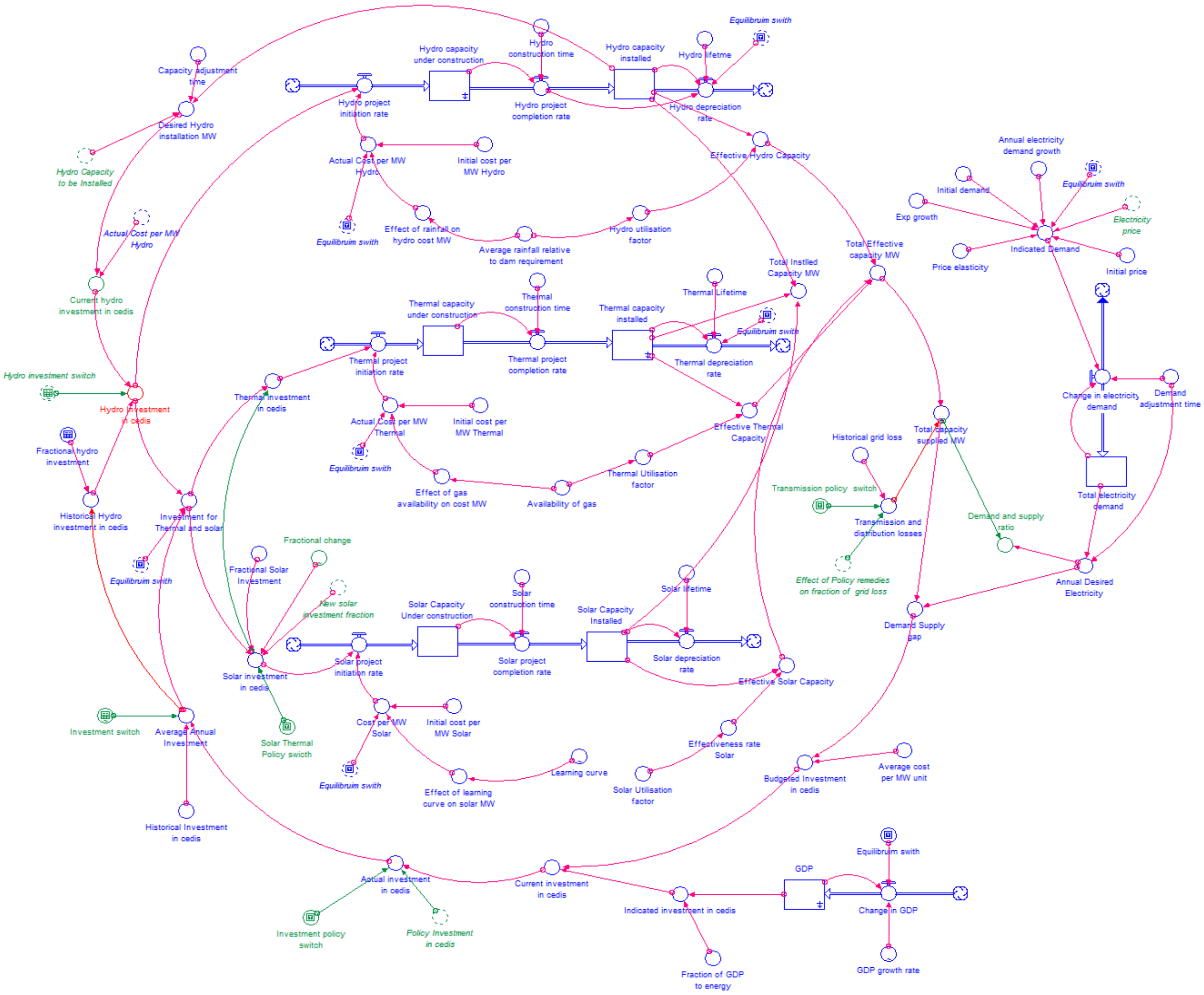
Appendix

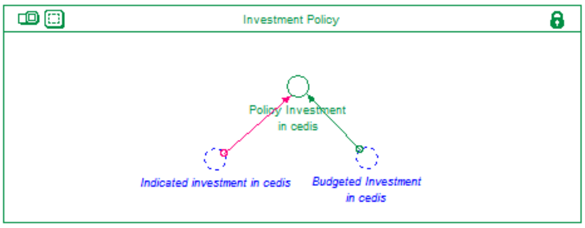
Appendix 1: Annual Electricity Transmission and distribution losses

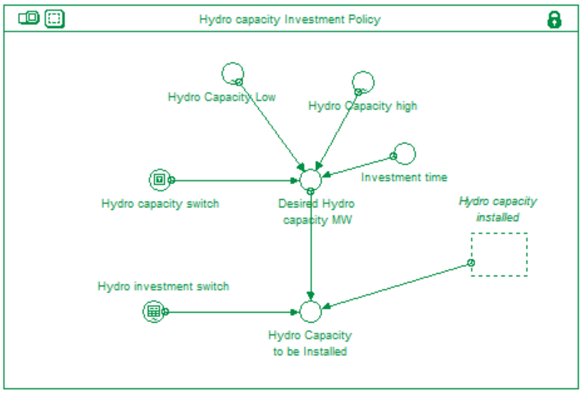


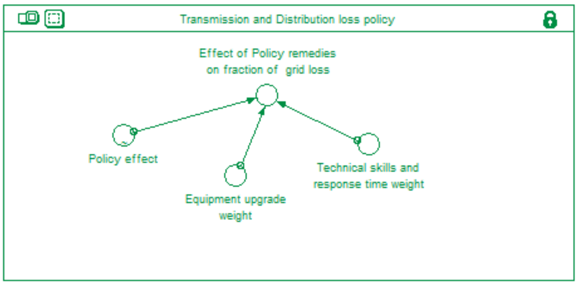
Complete Model Layout

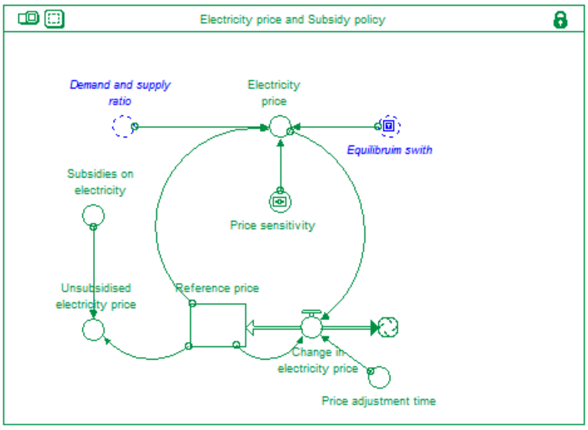


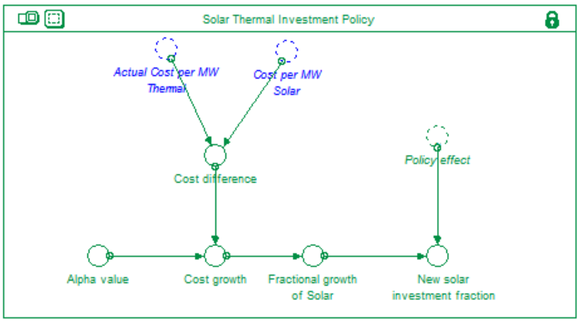
Policy structure











List of Equations in the Model

GDP(t) = GDP(t - dt) + (Change_in_GDP) * dt

INIT GDP = 20000000000

INFLOWS:

Change_in_GDP = GDP*GDP_growth_rate*Equilibruim_swith

Hydro_capacity_under_construction(t) = Hydro_capacity_under_construction(t - dt) + (Hydro_project__initiation_rate - Hydro_project__completion_rate) * dt

INIT Hydro_capacity_under_construction = 0

INFLOWS:

Hydro_project__initiation_rate = Hydro_Investment__in_cedis/Actual_Cost_per_MW__Hydro

OUTFLOWS:

Hydro_project__completion_rate = Hydro_capacity_under_construction/Hydro_construction_time

Thermal_capacity_installed(t) = Thermal_capacity_installed(t - dt) + (Thermal_project_completion_rate - Thermal_depreciation_rate) * dt

INIT Thermal_capacity_installed = 100

INFLOWS:

Thermal_project_completion_rate = Thermal_capacity__under_construction/Thermal_construction_time

OUTFLOWS:

Thermal_depreciation_rate = Thermal_capacity_installed/Thermal_Lifetime*Equilibruim_swith

Hydro_capacity__installed(t) = Hydro_capacity__installed(t - dt) + (Hydro_project__completion_rate - Hydro_depreciation_rate) * dt

INIT Hydro_capacity__installed = 1072

INFLOWS:

Hydro_project__completion_rate = Hydro_capacity_under_construction/Hydro_construction_time

OUTFLOWS:

Hydro_depreciation_rate = Equilibruim_swith*(Hydro_capacity__installed/Hydro_lifetme)+Hydro_project__completion_rate*(1-Equilibruim_swith)

Reference_price(t) = Reference_price(t - dt) + (Change_in__electricity_price) * dt

INIT Reference_price = Initial_price

INFLOWS:

Change_in__electricity_price = (Electricity_price-Reference_price)/Price_adjustment_time

Solar_Capacity_Under_construction(t) = Solar_Capacity_Under_construction(t - dt) + (Solar_project__initiation_rate - Solar_project__completion_rate) * dt

INIT Solar_Capacity_Under_construction = 0

INFLOWS:

Solar_project__initiation_rate = Solar_investment_in_cedis/Cost_per_MW_Solar

OUTFLOWS:

Solar_project__completion_rate = Solar_Capacity_Under_construction/Solar__construction_time

Solar_Capacity__Installed(t) = Solar_Capacity__Installed(t - dt) + (Solar_project__completion_rate - Solar_depreciation_rate) * dt

INIT Solar_Capacity__Installed = 0

INFLOWS:

Solar_project__completion_rate = Solar_Capacity_Under_construction/Solar__construction_time

OUTFLOWS:

Solar_depreciation_rate = Solar_Capacity__Installed/Solar_lifetime

Thermal_capacity__under_construction(t) = Thermal_capacity__under_construction(t - dt) + (Thermal_project__initiation_rate - Thermal_project_completion_rate) * dt

INIT Thermal_capacity__under_construction = 0

INFLOWS:

Thermal_project__initiation_rate = Thermal_investment_in_cedis/Actual_Cost_per_MW__Thermal

OUTFLOWS:

Thermal_project_completion_rate = Thermal_capacity__under_construction/Thermal_construction_time

Total_electricity__demand(t) = Total_electricity__demand(t - dt) + (Change_in_electricity__demand) * dt

INIT Total_electricity__demand = Initial_demand

INFLOWS:

Change_in_electricity__demand = (Indicated_Demand-Total_electricity__demand)/Demand__adjustment_time

Actual_Cost_per_MW__Hydro = Initial_cost_per__MW_Hydro+(Initial_cost_per__MW_Hydro*Effect_of_rainfall_on_hydro_cost_MW*Equilibruim_swith)

Actual_Cost_per_MW__Thermal = Initial_cost_per_MW_Thermal*(1+Effect_of_gas_availability_on_cost_MW*Equilibruim_swith)

Actual_investment_in_cedis = Policy_Investment__in_cedis*Investment_policy_switch+Current_investment__in_cedis*(1-Investment_policy_switch)

Alpha_value = 1e-06

Annual_Desired_Electricity = Total_electricity__demand/Demand__adjustment_time

Annual_electricity__demand_growth = 0.06

Availability_of_gas = 0.72

Average_Annual__Investment = Historical_Investment_in_cedis*(1-Investment_switch)+Actual_investment_in_cedis*Investment_switch

Average_cost_per_MW_unit = 3333000

Average_rainfall_relative__to_dam_requirement = 0.9

Budgeted_Investment_in_cedis = Demand_Supply_gap*Average_cost_per_MW_unit

Capacity_adjustment_time = 1

Cost_difference = Cost_per_MW_Solar-Actual_Cost_per_MW__Thermal

Cost_growth = Alpha_value*Cost_difference

Cost_per_MW_Solar = Initial_cost_per_MW_Solar*(1-Equilibruim_swith)+(Initial_cost_per_MW_Solar*Effect_of_learning_curve_on_solar_MW) *Equilibruim_swith

Current_hydro__investment_in_cedis = 0+ STEP(Desired_Hydro__installation_MW*Actual_Cost_per_MW__Hydro,2015)

Current_investment__in_cedis = MIN(Budgeted_Investment_in_cedis,Indicated_investment_in_cedis)

Demand_and_supply_ratio = Annual_Desired_Electricity/Total_capacity_supplied_MW

Demand_Supply_gap = Annual_Desired_Electricity-Total_capacity_supplied_MW

Demand__adjustment_time = 1

Desired_Hydro__capacity_MW = ((Hydro_Capacity_high*Hydro_capacity_switch)+Hydro_Capacity_Low*(1-Hydro_capacity_switch))*Investment_time

Desired_Hydro__installation_MW = (Hydro_Capacity_to_be_Installed-Hydro_capacity__installed)/Capacity_adjustment_time

Effectiveness_rate_Solar = Solar_Utilisation__factor

Effective_Electricity_Capacity_Data_MW = GRAPH(TIME)

(2000, 993), (2001, 1086), (2002, 1102), (2003, 1107), (2004, 1151), (2005, 1211), (2006, 1211), (2007, 1255), (2008, 1287), (2009, 1359), (2010, 1516), (2011, 1539), (2012, 1676), (2013, 1785), (2014, 1893), (2015, 1893), (2016, 1892), (2017, 1892), (2018, 1892), (2019, 1892), (2020, 1892), (2021, 1892), (2022, 1892), (2023, 1892), (2024, 1892), (2025, 1892), (2026, 1892), (2027, 1892), (2028, 1892), (2029, 1892), (2030, 1892)

Effective_Hydro_Capacity = Hydro_capacity__installed*Hydro_utilisation_factor

Effective_Solar_Capacity = Effectiveness_rate_Solar*Solar_Capacity__Installed

Effective_Thermal__Capacity = Thermal_capacity_installed*Thermal_Utilisation__factor

Effect_of_gas_availability_on_cost_MW = (1-Availability_of_gas)

Effect_of_learning_curve_on_solar_MW = (1-Learning_curve)

Effect_of_Policy_remedies_on_fraction_of__grid_loss = Policy_effect*(Equipment_upgrade_weight+Technical_skills_and__response_time_weight)

Effect_of_rainfall_on_hydro_cost_MW = (1-Average_rainfall_relative__to_dam_requirement)

Electricity_Demand__Data_in_MW = GRAPH(TIME)

(2000, 1161), (2001, 1181), (2002, 1227), (2003, 1235), (2004, 1249), (2005, 1325), (2006, 1333), (2007, 1274), (2008, 1327), (2009, 1423), (2010, 1556), (2011, 1665), (2012, 1729), (2013, 1943), (2014, 2000), (2015, 2000), (2016, 2000), (2017, 2000), (2018, 2000), (2019, 2000), (2020, 2000), (2021, 2000), (2022, 2000), (2023, 2000), (2024, 2000), (2025, 2000), (2026, 2000), (2027, 2000), (2028, 2000), (2029, 2000), (2030, 2000)

Electricity_price = Equilibruim_swith*(Reference_price*(Demand_and_supply_ratio^Price_sensitivity))+Reference_price*(1-Equilibruim_swith)

Equilibruim_swith = 1

Equipment_upgrade_weight = 0.3

Exp_growth = EXP(0.06*(time-2000))

Fractional_change = GRAPH(TIME)

(2000, 1.00), (2001, 1.00), (2002, 1.00), (2003, 1.00), (2004, 1.00), (2005, 1.00), (2006, 1.00), (2007, 1.00), (2008, 1.00), (2009, 1.00), (2010, 1.00), (2011, 1.00), (2012, 1.00), (2013, 1.00), (2014, 1.00), (2015, 0.00), (2016, 0.00), (2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00), (2021, 0.00), (2022, 0.00), (2023, 0.00), (2024, 0.00), (2025, 0.00), (2026, 0.00), (2027, 0.00), (2028, 0.00), (2029, 0.00), (2030, 0.00)

Fractional_growth__of_Solar = 1/(1+EXP(Cost_growth))

Fractional_hydro__investment = 0.4

Fractional_Solar__Investment = 0.01

Fraction_of_GDP__to_energy = 0.015

Gap_Data = Electricity_Demand__Data_in_MW-Effective_Electricity_Capacity_Data_MW

GDP_growth_rate = GRAPH(TIME)

(2000, 0.0387), (2001, 0.0425), (2002, 0.0514), (2003, 0.0584), (2004, 0.0603), (2005, 0.0603), (2006, 0.0717), (2007, 0.0787), (2008, 0.0959), (2009, 0.0986), (2010, 0.0986), (2011, 0.14), (2012, 0.0986), (2013, 0.0986), (2014, 0.0804), (2015, 0.0622), (2016, 0.0615), (2017, 0.0615), (2018, 0.0615), (2019, 0.0615), (2020, 0.0615), (2021, 0.0615), (2022, 0.0615), (2023, 0.0615), (2024, 0.0615), (2025, 0.0615), (2026, 0.0615), (2027, 0.0615), (2028, 0.0615), (2029, 0.0615), (2030, 0.0615)

Historical_grid_loss = 0.2

Historical_Hydro_investment_in_cedis = Fractional_hydro__investment*Average_Annual__Investment

Historical_Investment_in_cedis = 550000000

Hydro_Capacity_high = GRAPH(TIME)

(2015, 1585), (2016, 1644), (2017, 1702), (2018, 1772), (2019, 1831), (2020, 1864), (2021, 1885), (2022, 1904), (2023, 1928), (2024, 1943), (2025, 1959), (2026, 1974), (2027, 1984), (2028, 1992), (2029, 2000), (2030, 2000)

Hydro_Capacity_Low = GRAPH(TIME)

(2015, 1585), (2016, 1585), (2017, 1585), (2018, 1585), (2019, 1585), (2020, 1585), (2021, 1585), (2022, 1585), (2023, 1585), (2024, 1585), (2025, 1585), (2026, 1585), (2027, 1585), (2028, 1585), (2029, 1585), (2030, 1585)

Hydro_capacity_switch = 1

Hydro_Capacity_to_be_Installed = (Desired_Hydro__capacity_MW*Hydro_investment_switch)+Hydro_capacity__installed*(1-Hydro_investment_switch)

Hydro_construction_time = 3

Hydro_investment_switch = GRAPH(TIME)

(2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 0.00), (2004, 0.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2015, 1.00), (2016, 1.00), (2017, 1.00), (2018, 1.00), (2019, 1.00), (2020, 1.00), (2021, 1.00), (2022, 1.00), (2023, 1.00), (2024, 1.00), (2025, 1.00), (2026, 1.00), (2027, 1.00), (2028, 1.00), (2029, 1.00), (2030, 1.00)

Hydro_Investment__in_cedis = Historical_Hydro_investment_in_cedis*(1-Hydro_investment_switch)+Current_hydro__investment_in_cedis*Hydro_investment_switch

Hydro_lifetme = 100

Hydro_utilisation_factor = Average_rainfall_relative__to_dam_requirement

Indicated_Demand = Equilibruim_swith*(Initial_demand*(1+Annual_electricity__demand_growth)*Exp_growth*((Electricity_price/Initial_price)^Price_elasticity))+Initial_demand*(1-Equilibruim_swith)

Indicated_investment_in_cedis = Fraction_of_GDP__to_energy*GDP

Initial_cost_per_MW_Solar = 5000000

Initial_cost_per_MW_Thermal = 2600000

Initial_cost_per__MW_Hydro = 2800000

Initial_demand = 1161

Initial_price = 0.017

Investment_for__Thermal_and_solar = Equilibruim_swith*(Average_Annual__Investment-Hydro_Investment__in_cedis)

Investment_policy_switch = 1

Investment_switch = GRAPH(TIME)

(2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 0.00), (2004, 0.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2015, 1.00), (2016, 1.00), (2017, 1.00), (2018, 1.00), (2019, 1.00), (2020, 1.00), (2021, 1.00), (2022, 1.00), (2023, 1.00), (2024, 1.00), (2025, 1.00), (2026, 1.00), (2027, 1.00), (2028, 1.00), (2029, 1.00), (2030, 0.00)

Investment_time = 1

Learning_curve = GRAPH(TIME)

(2000, 0.00317), (2001, 0.00952), (2002, 0.0159), (2003, 0.0222), (2004, 0.0222), (2005, 0.0254), (2006, 0.0286), (2007, 0.0317), (2008, 0.0413), (2009, 0.0413), (2010, 0.0444), (2011, 0.0508), (2012, 0.054), (2013, 0.0603), (2014, 0.0667), (2015, 0.0762), (2016, 0.0825), (2017, 0.0889), (2018, 0.0952), (2019, 0.0984), (2020, 0.105), (2021, 0.111), (2022, 0.127), (2023, 0.146), (2024, 0.165), (2025, 0.175), (2026, 0.2), (2027, 0.219), (2028, 0.26), (2029, 0.284), (2030, 0.301)

New_solar__investment_fraction = Fractional_growth__of_Solar*Policy_effect

New_Thermal_fraction = (1-New_solar__investment_fraction)*Policy_effect

Policy_effect = GRAPH(TIME)

(2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 0.00), (2004, 0.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2015, 1.00), (2016, 1.00), (2017, 1.00), (2018, 1.00), (2019, 1.00), (2020, 1.00), (2021, 1.00), (2022, 1.00), (2023, 1.00), (2024, 1.00), (2025, 1.00), (2026, 1.00), (2027, 1.00), (2028, 1.00), (2029, 1.00), (2030, 1.00)

Policy_Investment__in_cedis = IF Indicated_investment_in_cedis>Budgeted_Investment_in_cedis THEN Indicated_investment_in_cedis ELSE Budgeted_Investment_in_cedis

Price_adjustment_time = 1

Price_elasticity = -0.38

Price_sensitivity = 0.8

Solar_investment_in_cedis = IF Solar_Thermal_Policy_swicth =1 THEN (Investment_for__Thermal_and_solar*Fractional_Solar__Investment*Fractional_change)+(Investment_for__Thermal_and_solar*New_solar__investment_fraction) ELSE (Investment_for__Thermal_and_solar*Fractional_Solar__Investment)

Solar_lifetime = 30

Solar_Thermal_Policy_swicth = 1

Solar_Utilisation__factor = 1

Solar__construction_time = 3

Subsidies_on__electricity = 0.25

Technical_skills_and__response_time_weight = 0.2

Thermal_construction_time = 2

Thermal_investment_in_cedis = Investment_for__Thermal_and_solar-Solar_investment_in_cedis

Thermal_Lifetime = 50

Thermal_Utilisation__factor = Availability_of_gas

Total_capacity_supplied_MW = Total_Effective__capacity_MW*(1-Transmission_and__distribution_losses)

Total_Effective__capacity_MW = Effective_Hydro_Capacity+Effective_Thermal__Capacity+Effective_Solar_Capacity

Total_Instlled__Capacity_MW = Hydro_capacity__installed+Solar_Capacity__Installed+Thermal_capacity_installed

Transmission_and__distribution_losses = Historical_grid_loss*(1-Transmission_policy__switch)+(Historical_grid_loss*Transmission_policy__switch)-(Effect_of_Policy_remedies_on_fraction_of__grid_loss*Transmission_policy__switch*Historical_grid_loss)

Transmission_policy__switch = 1

Unsubsidised__electricity_price = Reference_price*(1+Subsidies_on__electricity)