

A Dynamic Approach to Understanding
the Nexus between Electric Power Demand
and
Economic Growth,
Using a Generic Electricity Model:
The Case of Ghana

by

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Thesis

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Abstract

The debate about the interplay between energy and economic growth continues unabated without any indication of a consensus being reached. While some research work point to a unidirectional relationship between energy consumption and economic growth, others point to a bi-directional relationship between the two. The contrasting results are due to the use of different data sets, alternative methodologies; and different countries' characteristics such as indigenous energy supplies, different political/economic histories, political arrangements, culture, et-cetera (Ozturk 2010).

In Ghana, Wolde-Rufael (2009) and Akinlo (2008) found a bi-directional relationship between energy consumption and economic growth. They suggested that energy consumption and growth are reinforcing. But no real quantity grows forever (Sterman, 2000 p. 285). This paper uses System Dynamics tools to explore how feedbacks, delays and nonlinearities play out between energy (with specific reference to electricity) and economic growth; and seeks to provide policy makers in the power industry an alternative capacity planning tool.

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Introduction

Electricity as a form of energy plays a very important role not only in industrial production of goods and services but also in households' activities. Electricity has become an integral part of production in recent years such that the lack of it tends to stifle production. Providing clean, adequate, reliable and efficient electricity by governments the world over has been an obvious goal for many countries intending to boost their economy whether through heavy or light industrialization, or even through the service industry. Widespread industrialisation of the Norwegian economy was preceded with the massive introduction of electricity (Venneslan 2009), and thus electricity, as a modern form of energy, is seen to facilitate technological advancement (Schurr 1990). Previous studies on the causal relationship between energy consumption and economic growth in Ghana suggest that energy consumption reinforces economic growth and vice versa (Wolde-Rufael (2009), Akinlo (2008)).

The purpose of this project is to attempt to provide some understanding of the electricity sector in Ghana with a generic System Dynamic model. The model attempts to assess the interrelationship between the power sector on one hand and population in conjunction with the economic sector (GDP) on the other hand. The model explores delays, nonlinearities, and feedback processes in assessing the interplay between electricity and economic growth.

The paper is organised into seven sections. The first section takes a look at some of the literature in the broad energy sector and then narrowly looks at literature in the electricity sector and how both interrelate to the economy. Trends in the world energy production and consumption are reviewed, as well as trends in Africa and then those in Ghana.

The second section discusses the dynamic problem associated with the current electricity production capacity in Ghana. Data sources are discussed in the second section. The fourth section describes the hypothesis with the aid system dynamic tools such as *causal loop diagrams*, and *Stocks and Flow diagrams*, placing emphasis on feedbacks, delays and nonlinearities. The fifth section provides analysis of the model through tests of the model. Analysis of the policy structure is carried out in the sixth section. Policy implementation challenges are discussed and conclusions are drawn in the seventh and eighth sections respectively.

1. LITERATURE REVIEW

Global Trends in Energy usage

Electricity, viewed as a General Purpose Technology (GPT), plays an important role in national development. Many nations achieved industrial breakthrough through the consistent investment in electricity production. Norway became a fully-fledged industrialised economy in the first decades of the twentieth century through the widespread introduction of electricity (Venneslan 2009).

As reported in the 2009 edition of World Energy Outlook, world electricity demand is projected to grow at an annual rate of 2.5% to 2030. According to the report, the consistent growth in energy needs for power generation worldwide is the main driver of demand for fossil fuel (mainly, coal and gas). This calls for huge investments in power plants to ensure adequate resource availability. It is expected that additions to total power-generation capacity will be about 4800 gigawatts (GW) by 2030—about five times in excess of the existing capacity of the United States; and the non-OECD countries will be responsible for this growth, while demand in OECD countries falls. Meanwhile, estimates show that fossil fuels remain the dominant sources of primary energy worldwide, with coal seeing the biggest increase in demand for the projection period 2008 to 2030, followed by gas and oil. For reason that it is the dominant fuel used in the power sector, coal is considered the “backbone” fuel in the power sector, with its share of global generation mix rising three percentage point to 44% in 2030. However, it is reported that oil is the single largest fuel in the primary fuel mix, demand of which is projected to grow by 1% per year on average, from 85 million barrels per day (mb/d) in 2008 to 105 mb/d in 2030. All the projected growth comes from the non-OECD countries. And between 2007 and 2030 it is projected that world primary energy demand could increase by 1.5% per year from over 12 000 million tonnes of oil equivalent (Mtoe) to 16800 Mtoe. This represents an increase of 40% over the period, with Developing Asian countries being the main drivers of this growth followed by the Middle East (WEO 2009).

While global primary energy demand is projected to increase at an annual rate of 1.6%, over 70% of the estimated increase in demand (from 2004-2030) comes from developing countries; and population and economic growth are the main drivers (IEA, 2006; WEO, 2006). According to the 2006 World Energy Outlook (WEO) report almost half of the increase in global primary energy use goes to generating electricity.

Other sources of renewable energy sources are gaining currency among world leaders as there appears to be a gradual global shift from hydro power to other renewable energy technologies for power generation. In terms of world total power output, while the share of hydropower drops from 16% to 14% for the projection period 2007 to 2030; that of non-hydro modern renewable energy technologies (wind, solar, geothermal, tide and wave energy, and bio-energy) rises from 2.5% in 2007 to 8.6% (IEA, 2009; WEO, 2009).

Trends in energy consumption and electricity production in Africa

Africa possesses immense energy potential, this notwithstanding, “energy consumption in general and electricity consumption in particular is very low” (Karekezi and Kimani 2002). Compared to the rest of the world, in the year 2007 Africa recorded only 5.6% share (from 3.7% in 1973) of the world’s total final energy consumption (IEA 2009); while its share of the world’s electricity production is less than 4% in 2007 after more than three decades (increased from 1.8% in 1973 to 3.1% in 2007) figure 1.

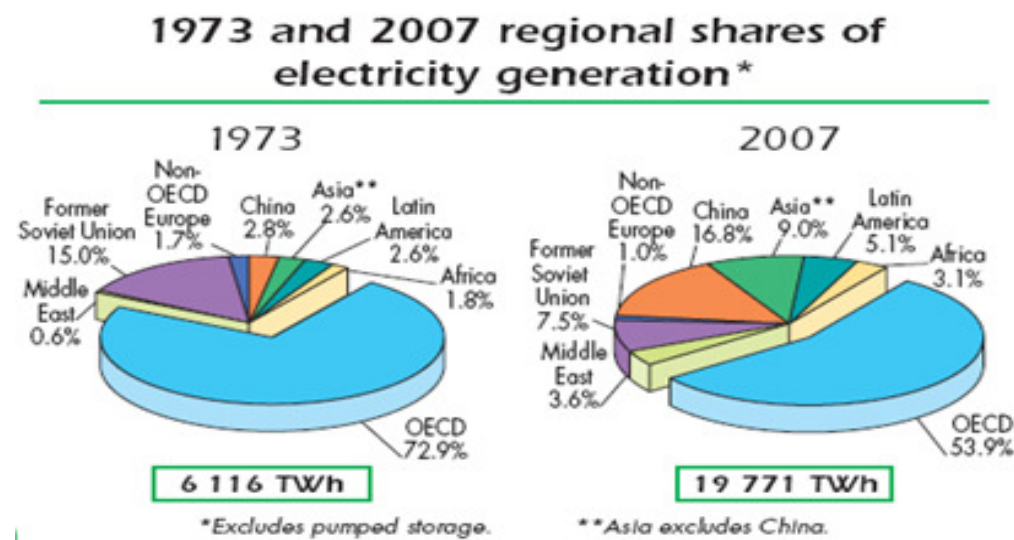


Figure 1: Electricity generation by region

Source: International Energy Agency, 2009

Exploitable hydropower capacity, as well, in African countries is vast, but less than 7% has been harnessed—one of the world’s lowest figures (Karekezi 2002). Compared to the rest of the world, Africa’s share of hydro production is only 3.1% in 2007 (IEA 2009), inching marginally from 2.2% in 1973. The use of other forms of energy has gained currency among

the people of the region, partly because modern energy is either unavailable, or its access is limited. Traditional biomass energy accounts for 70%-90% of primary energy supply (Karekezi 2002). In Ghana, for instance, biomass accounts for more than 60% of total energy used in Ghana (Ghana Energy Commission (EC), 2006). Majority of people without access to electricity in Africa live in the rural areas. According to IEA estimates 1.5 billion of the world's population lack access to electricity, and of this number 85% live in rural areas mainly in Sub-Saharan Africa and South Asia. Describing the dire electricity connectivity in Africa, Wolde-Rufael (2004) indicated that than 500 million Africans are still without access to electricity Wolde-Rufael. IEA on its part emphasises that Africa has the lowest electrification rate of any major world region, with only 23% of its population electrified compared to the world average of 73% (IEA, 2002). The poverty level of the people of Africa could be explained partly by the lack of access to clean, reliable modern energy, a claim that IEA endorses by emphasising that:

“expanding access to modern energy is a necessary condition for human development”

The United Nations Industrial Development Organisation (UNIDO) expressed this view through this emphatic statement that:

“Energy access is imperative to combating poverty”¹.

Access to modern and clean energy such as electricity is a world-wide phenomenon and the world's poor, living in rural areas, are the most affected. IEA estimates that about one-fifth of the world's population, numbering about 1.5 billion people, still lack access to electricity and *“some 85% of those people live in rural areas, mainly in Sub-Saharan Africa and Asia.”* Extending electricity supply to all these deprived communities involves a hefty investment annually—investments in power-generating plants, transmission grids as well as distribution networks. However it is estimated that by 2030 only about 200million people of the 1.5billion will have access to electricity. This is expected to take place in Africa.

It is expected that “with appropriate policies, universal electricity access could be achieved with additional annual investment worldwide of \$35billion (in year-2008 dollars) through to 2030” (IEA, 2009, WEO 2009).

¹ KandehK.Yumkella, Director General of United Nations Industrial Development Organization (UNIDO), stressed this point during the September 2010 UN General Assembly's Millennium Development Goal review summit. See <http://www.iisd.ca/ymb/mdg/summit2010/> , Final Issue, Volume 153, No. 9, Saturday, 25 September 2010

The debate about the causal link between energy consumption and economic growth continues unabated. Research findings have established mixed relationships between energy use and economic development. While some findings point to a *unidirectional* causal relationship linking energy use to economic development or vice-versa, in which case energy use triggers economic growth or vice-versa; others suggest a *bi-directional* relationship between the two, suggesting that both energy use and economic growth reinforce each other's growth. The contrasting results are as a result of different data sets, alternative methodologies and different countries' characteristics such as indigenous energy supplies, different political/economic histories, political arrangements, culture, et-ce tera (Ozturk 2010).

Wolde-Rufael (2009) and (Akinlo 2008) found that there is a positive reinforcing relationship between energy consumption and economic growth in Ghana and other African countries such as Gambia, Gabon, Senegal, Togo and Zimbabwe; this result suggests that energy consumption stimulates economic growth, and economic growth as well stimulates energy consumption. It is, however, not explicit in Wolde-Rufael (2009) what proportion of the total energy consumed (between 1971-2004) in his selected countries relate to electricity or electricity generation. Incidentally, (Wolde-Rufael 2006) pointed out that less than 4% of Africa's energy consumption is attributable to electricity. However, long run causal relationship is established between electricity consumption and economic growth in some African countries: Egypt, Morocco and Gabon have recorded bi-directional causal relationship between Electricity use and Economic growth (Wolde-Rufael 2006), implying that more electricity use induce economic growth, and the more the economy grows the more electricity is used.

In order to ascertain the important role energy plays in the production of goods and services, many studies have attempted to include energy as an additional factor of production -in addition to capital and labor- (see Wolde-Rufael, 2009; Stern, 2000). It turns out that the importance of energy, and for that matter, electricity cannot be downplayed in the production process. Electricity plays a critical role in production and in many cases its availability sets the stage for innovation that lead to enhanced production. Surge in industrial productivity is attributed, inter alia to the diffusion of General Purpose Technology. Schurr et al, (1990) describe electricity as an agent of technological progress and emphasises its strong impacts and importance in both our homes and in the industrial sector. Empirical evidence suggests

that electrification and productivity growth are strongly related (US National Research Council², 1988) and this relationship is positive in a wide range of industries

Meanwhile (Lee 2005) investigations in 18 developing countries (including Ghana and Kenya) revealed that “Energy consumption is found to Granger cause GDP, but not vice versa”. Interpreting Lee’s results could mean that implementing energy conservation policy could have adverse effect on GDP. Ammah-Tagoe (1990) found causality from GDP to energy use in Ghana (mentioned in (Stern 2000)).

However, in Egypt, Ivory Coast, Morocco, Nigeria, Senegal, Sudan, Tunisia and Zambia, there exist a unidirectional causality from economic growth to energy consumption(Wolde-Rufael 2009); where economic growth is said to trigger energy consumption but not otherwise.

In Tanzania, (Odhiambo 2009) found that there exists ‘*distinct unidirectional causal flow from total energy consumption to economic growth*’; and suggested that there is a short run causal flow from electricity consumption to economic growth. Odhiambo 2009, however, concludes from their research work that energy consumption in general induces economic growth in Tanzania. It was not mentioned, in their work, what effect economic growth has on energy consumption in Tanzania.

Emissions

Energy production is the hub of greenhouse gas emission. The debate on climate change continues unabated as the world continues to face the challenge of greenhouse-gas emissions with energy being at the heart of the problem. Energy consumption continues to increase. To chart a path for a truly sustainable energy, “*the 15th Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UFCCC) in Copenhagen (December 2009) presents a decisive opportunity to negotiate a successor treaty to the Kyoto Protocol*” (IEA2009). But the Copenhagen protocol ended without a binding legal agreement on the world leaders to cut down on emissions (BBC, December 2009). “*Energy-related carbon-dioxide (CO₂) emissions in 2009 would be below what they have been, had the recession not occurred; in that the “...recession provided an unprecedented window of*

² This conclusion was contained in a report of the Committee on Electricity in Economic Growth in 1986, under the umbrella body of National Research Council (U.S).

opportunity (though relatively narrow) to take action to concentrate investments on low-carbon technology.” (IEA 2009).

Overview of Energy in Ghana

The main sources of energy in Ghana are woodfuels (also referred to as biomass), hydro electric power, solar, and fossil fuels. Woodfuels constitute a greater proportion of the primary indigenous energy. According to the Ghana Energy Commission, between year 2000 and 2004 the share of woodfuel to total energy supply increased from about 60% to 67%, while Electricity reduced from about 11% to 6%; and share of petroleum product dropped from 29% to 27% for the same period.

Electricity Industry in Ghana

The Electric power industry is a regulated monopoly, which comprises six public institutions with separate operational and regulatory functions. These are the Ministry of Energy (MOE), Energy Commission (EC), Public Utility Regulatory Commission (PURC), Volta River Authority (VRA), Electricity Company of Ghana (ECG) and the Northern Electricity Department (NED)³.

The MOE is responsible for the formulating, monitoring and evaluating policies programs and projects in the energy sector (which includes the power sector). The MOE has an oversight responsibility in the energy sector in general.

The regulatory functions of the power sector rest with the EC and the PURC. Not only is the EC responsible for technical regulation of the energy supply sector, which includes licensing of operators; but also advising the Minister of Energy on national policies for the efficient, economical and safe supply of electricity, natural gas and petroleum products.

On the other hand, the PURC has the responsibility of approving rates of utilities sold by the distribution companies to the public. The PURC sets these utility rates in consultation with all the stakeholders in the power sub-sector, including the power generators, distributors and representatives of major consumers. In addition the PURC monitors the quality of electricity

³ NED is a subsidiary of VRA and is responsible for the distribution of electricity in the Northern Sector of Ghana. It's operations covers the Brong Ahafo, Northern, Upper East and Upper West regions.

services delivered to customers. The Utility companies that the PURC regulates include the Electricity Company of Ghana, and Volta River Authority with its subsidiary Northern Electricity Department. Any company that will operate in the gas sector (yet to develop following the commencement of oil production in Ghana) is more likely to come under the control of PURC. Apart from rates approval and regulation of the utility companies, the PURC also perform such functions as organising Public Awareness Programs (PAP) as well as Monitoring of Utilities.

The VRA is responsible for the generation of electricity, while ECG and NED are responsible for power distribution. Until August 2008 when Ghana Grid Company Limited (GRIDCo) became operational, VRA was performing both functions of generating and transmitting electricity. The VRA owns and operates the two Hydro Power Stations at Kpong and Akosombo, as well as the Takoradi Thermal Plant (TAPCO). Besides, the VRA is a part owner of the Takoradi International Power Company (TIPC), which runs a thermal plant.

Electricity distribution is carried out by ECG and NED. While ECG has the southern part of Ghana as its operational zone (which include the Greater Accra, Eastern, Western, Central, Volta and Ashanti regions); NED's operation covers the northern part of Ghana.

Electricity Transmission functions as of August 2008 came under the purview of GRIDCo. The separation of power Transmission function from generation was, among other reasons, to promote competition in the power market. GRIDCo's establishment was also intended to "provide transparent, non-discriminatory and open access to the transmission grid for all the participants in the power market particularly, power generators and bulk consumers and thus bring about efficiency in power delivery" (GRIDCo). Specifically, GRIDCo was therefore tasked to⁴:

- Undertake economic dispatch and transmission of electricity from wholesale suppliers (generating companies) to bulk customers, which include the Electricity Company of Ghana (ECG), Northern Electricity Department (NED) and the Mines;
- Provide fair and non-discriminatory transmission services to all power market participants;

⁴ www.gridcogh.com

- Acquire, own and manage assets, facilities and systems required to transmit electrical energy;
- Provide metering and billing services to bulk customers;
- Carry out transmission system planning and implement necessary investments to provide the capacity to reliably transmit electric energy; and manage the Wholesale Power Market.

The core functions of the industry players in the power sector is summarised in Table 1.

INSTITUTION	CORE FUNCTION
MINISTRY OF ENERGY	Government mouthpiece and responsible for energy Policy formulation
ENERGY COMMISSION	Energy Policy Advisory, planning, technical regulation and monitoring
PUBLIC UTILITY REGULATORY COMMISSION	Utility Tariff Regulation
VOLTA RIVER AUTHORITY	Electricity Generation (and erstwhile Transmission)
NORTHERN ELECTRICITY DEPARTMENT	Electricity Distribution
ENERGY FOUNDATION	Promotion of Energy Efficiency and Conservation
GHANA GRID COMPANY LIMITED	Electricity Transmission

Table 1 Institutions in the Power sub-sector

Sources: Energy Commission, Ministry of Energy

History of power supply

The Akosombo Dam

In 1915, Sir Albert Ernest Kitson, of the Gold Coast Geological Survey Department, proposed the construction of a hydro-electric dam on the Volta River. After several studies, he came up with recommendations to build dams not only on the Black Volta, but also mini-dams on some of the coastal rivers such as Tano, Pra and several others. The purpose of the dam at Akosombo was ostensibly for industrial use, as the electricity to be generated was to be used mainly to process the bauxite deposits that Kitson discovered in the Kwahu Plateau. At the time there was little demand for electrical power. In order to create the demand, the construction of an aluminium smelter was included in the project. That was what gave birth to the Volta Aluminium Company (VALCO). Kitson envisaged the Bui dam to serve the need of rail transportation to the north in the future. After independence in 1957, the first stage of construction of the Akosombo dam began upon the establishment of the Volta River Project. The first unit (ie made up of four turbines with total installed capacity of 588MW) of Akosombo Generation Station was completed in 1965 and officially commissioned in January 1966 by Ghana's first President, Osagyefo Dr. Kwame Nkrumah, this being one of his attempt to rapidly industrialise the economy. The production of hydro-electric power on commercial basis began in 1965, "marking an important step for industrialisation and economic growth."⁵

Lake Volta, the largest man-made lake in the world, was created through this development. It covers an area of about 8500 km² and has a length of 400 km with a shoreline of 5500 km.

The second stage of the Volta River project was completed in 1972 with the addition of two generating units with total installed capacity of 324MW. The total installed capacity of the six-unit Akosombo Generation Plant increased to 912MW by end of 1972.

Akosombo Retrofit project

After running the Akosombo for nearly 30 years and producing electricity in commercial quantity for all these years, there was the need to carry out a thorough maintenance to ensure continuous reliable power supply to not only Ghana but also to neighbouring countries like Togo and Ivory Coast. The Akosombo Generation Retrofit Project was then launched in

⁵ Link: <http://www.vra.com/Power/akohydro.php>

1989. The retrofitting took place between October 1999 and March 2005. The main objective of the retrofitting was to:

“return the turbine/generator units to an "as new" condition replacing those parts which were beyond repair, to replace or renovate the auxiliary equipment, and to improve the powerhouse amenities and services....as well as to ensure that VRA..... operates safely in the future, with a minimum of outages and inconvenience to VRA's customers.”

Given that the dam was retrofitted with state-of-the-art technology, it revealed that the maximum output increased by 37% when compared to the original turbines’. Tests carried out confirmed that the performance of the retrofitted units “exceeded the guaranteed performance given by the Contractor”. This was a significant financial benefit to the VRA. At the end of the retrofit project in 2006 the Akosombo generation capacity increased from 912MW to 1020MW, an increase of 108MW that can be described as significant.

Kpong Dam

And then in 1982 the Kpong dam was completed to mark the third stage of the Volta River Project. It is located 21Km south of the Akosombo Dam with total installed capacity of 160MW, consisting of 4 units. This brought the total installed hydro-capacity to 1072MW as of 1982. The two dams run in tandem in order to optimise water use from the Volta River.

Thermal Plants

With total installed capacity of 550MW, the Takoradi Thermal Power Station (TTPS), owned and operated by the VRA, is located at Aboadze, some 17km east of Secondi Takoradi in the Western Region. Two thermal plants make up the TTPS. They are TAPCO (330MW) and TICO (220MW). As discussed earlier, the TAPCO is wholly owned by VRA, while TICO is partly owned. The Thermal Plant was built to complement the Akosombo and Kpong hydro in meeting the nation’s energy demands. In justifying the construction of the thermal plants, VRA explained that “Ghana’s current demand has outstripped the supply from the two hydro stations” and that the shortfall of the supply was going to be addressed by the thermal plants. The thermal plants have dual firing capacity: they run on both gas and oil, nonetheless, the primary fuel used for power generation is Light Crude Oil (LCO). Distillate Fuel Oil (DFO), used as secondary fuel, is normally used for start-up and shutdown of these plants. The thermal plants operate in two modes: combined cycle and simple cycle modes. The 330MW TAPCO combine cycle comprises two 110Megawatt combustion turbines that use either oil or gas to generate electrical energy; and in the process generate heat that is hot enough to heat

water into superheated steam to run a 110Megawatt steam turbine. The three generating units working in tandem gives it the name Combined cycle. The 220MW TICO thermal plant is a Simple Cycle unit, for reason that there is no steam turbine attached to it; hence the heat that it generate when in operation escapes into the air. It is reported that it will be soon converted into a combined cycle unit by adding to it a 110MW steam turbine. When completed that will bring the TICO installed capacity to 330.

The Bui Dam

The Bui Dam, currently under construction on the Black Volta River, was part of the Volta River Project in 1960, but was shelved after a change of government. Since then the Bui Gorge area was demarcated as a national park to prevent encroachment by human settlements. In 2007 a \$560 million⁶ financing was sought from China Exim Bank and the project was to be carried out by a Chinese company called Sinohydro. Some media report indicate that the project commenced in April 2008 and it is expected to be completed and commissioned in December 2012⁷.When completed, the Bui Dam will be the nation's third major hydro dam on the Volta River. That will bring the total hydro dam capacity to 1580 Mw.

The Power Supply chain

Electricity supply begins with the production sector that generates electricity from various sources such as hydro, thermal (which could be gas-fired, coal-fired, or fossil-fired plants). After production, the transmission infrastructure is used in transporting the power to energy-intensive industrial sectors (such as the mines, aluminium companies etc), as well as to the distribution sector. With its infrastructure, the distribution sector converts the power it receives from the transmission sector into forms that meet the requirements of its various classes of customers including the commercial and the residential sector.

Electricity Production and challenges

From the foregoing section, table 2 summarizes the total installed electricity capacity in Ghana:

⁶ <http://www.internationalrivers.org/en/africa/africa-other-projects>

⁷ <http://news.myjoyonline.com/politics/201102/60967.asp>

Plant	Installation		Gross Capacity (Megawatt)	Available capacity (Megawatt)	Net
	Year	Status			
Akosombo Hydro	1965/1972	Operating	1038 ⁸	1020	
Kpong Hydro	1982	Operating	160	148	
TAPCO	1997-2000	Operating	330	300	
TICO	2000	Operating	220	210	
Tema Diesel	1961/1962	Unavailable	30	-	
Power Barge	2000	Not commissioned	125	-	
Tema Thermal	Gas Not yet	Not yet built	330 or 900		
Bui Hydro	2007-date	In progress	400	-	
Total available				1678	

Table 2: Status of Power plants in Ghana as at 2006

Source: Adapted from Energy commission SNEP Report 2006, AnnexII of IV Electricity, pg 10

Sometimes for technical and/or climate-related reasons the full capacity of installed power plants is not harnessed. For instance, the 160MW capacity of the Kpong dam is limited to an output of 148MW as a result of a “rise in tail water elevation” when all four units are running. And, as for the thermal plants it may not be practically possible to tap into their full capacity partly due to high weather temperatures. In assessing the impact of climate change on the Volta Lake (Gyau-Boakye 2001) concludes that the rising average temperatures and declining rainfall levels results in the decline in lake water level especially during the period

⁸ This 1038MW gross capacity of the Akosombo generation station is inconsistent with earlier accounts herein and all other accounts we have come across which gave the capacity as 1020MW. Our interest, however, is on the actual capacity with which power is produced.

of their study (1971-1990). Apart from the observed rising temperatures, deforestation—resulting from human activities—along the banks of rivers that feed the lake, as well as along the Volta River, cannot be disregarded as one of the reasons that possibly accounts for the reductions in the water flow into the dam. In 2006 and around 1990 Akosombo Dam operated below its capacity as a result of shortage of water in the Volta Lake. It was a period of power crisis.

Electricity Transmission

GRIDCO's transmission system is currently made up of 53 substations with 4,315.5km long transmission lines (table 3) to carry electrical energy from the producer to the various consumers. Losses in transmission have been a challenge from the past. Electricity service reliability has deteriorated as a result. Some of the transmission losses are attributed to overloading the lines, and thus making them operate close to their thermal limit. The transmission loss benchmark set by the PURC of 2.8% has hardly been met over the years. Transmission losses have averaged 3% between 1990 and 2001, however 4.9% was recorded in 2003 (EC 2006). In order to enhance supply reliability and improve voltage stability nationwide, there is the need to expand the transmission infrastructure. Indeed, the transmission infrastructure has seen some improvements over the years—for instance there were 36 substations with about 4000km of transmission lines in year 2000 according to the erstwhile transmission company, VRA; and currently there are 53 substations with a little over 4000km substations (table 3). There are also reports of new transmission lines under construction.

Transmission	Length of Transmission Line (Kilometres)
330 kV	219.5
161 kV	3888.1
225 kV	73.4
69 kV	132.8
Total	4313.8Km

Table 3: State of Transmission Network

Source: author's construct, see www.gridcogh.com, 2011

Electricity Distribution

As mentioned earlier the two public institutions responsible for electricity distribution are the ECG and NED, both of which are not doing any better in terms of financial and operation performances. Deteriorating and inadequate distribution infrastructure has badly affected efficient and reliable power supply to customers over the years. ECG's high system losses "averaging 26% per annum is not helping matters" (EC 2006). Under the Power Sector Reform, ECG is to absorb NED to form one major distribution company. This merger is expected to address the myriad of resource-related bottlenecks contributing to the poor and underperformance of both utilities. Set benchmarks for a healthy distribution company are, on the average:

- 10% for sales growth
- 12% for return on capital employed
- 5% for Asset Turnover, and
- 10% for Interest cover (EC 2006)

ECG has not been running profitably enough: its sales growth measures 3.1% and 2.8% in year 1999 and 2000 respectively as against the benchmark of 10%. ECG's Return on Capital Employed (ROCE) and Asset turnover in year 2000 were 0.87% and 0.63% respectively. These variations cannot be described as marginal deviation from the bench benchmarks. Data

available to the EC indicate that ECG's Debt/Equity ratio has been over 300% with net loss margin in year 2000 nearly 70%. These are way above the sector averages of 50% for Debt/Equity ratio and 8% for net loss margin. A performing utility company is expected to record not more than 2 months for its Debtors' ratio, but in year 2000, ECG had between 6-7 months for its Debtors' ratio. Part of the problems accounting for ECG's financial woes has to do with its efficiency in revenue collection. Revenue collection efficiency has averaged about 81% between 2000 and 2001, below the PURC's threshold of 95%. Nearly 20% of revenue yearly remains uncollectible over the period? Figure 2 is a snapshot of some performance indicators of ECG: System losses averaging 26% over the years, possibly, attributable to the poor and deteriorating distribution infrastructure.

		2000	2001	2002	2003	2004
A	End User Tariff in US cents per unit	2.6	5.2	7.8	8.2	8.2
B	Units purchased from VRA in %	100	100	100	100	100
C	System losses in %	27	26	26	26	26
D=b - c	Units billed to customers in %	73	74	74	74	74
E	PURC Benchmark in %	82	82	82	82	82
f=d x a	Actual customer billing in US \$	1.9	3.8	5.8	6.1	NA
f=e x a	Expected customer billing in US \$	2.1	4.3	6.4	6.7	NA
G	Revenue collection efficiency in %	79	79	80	87	NA
H	PURC Benchmark in %	95	95	95	95	95
i=f x h	Expected revenue to be collected	1.8	3.6	5.5	5.8	NA
j=f x g	Actual Revenue collected	1.5	3.0	4.6	5.3	NA
K=j ÷ a	Units revenue collected	57.7	57.7	58.9	64.6	NA

Source: Adapted from ECG data, 2004

Figure 2: Revenue performance of ECG 2004

Source: Ghana Energy Commission SNEP 2006, Annex II of IV Electricity, pg 14

These statistics are alarming and call for concern, however, present records show that the ECG has marginally improved over its year 2000 performance. The introduction of Pre-paid meters to replace the old Credit meters is expected to resolve some of the revenue-related problems such as delay in payment of bills, uncollectible debt arising from the absconding or relocation of debtors.

Electricity consumption

Ghana's electricity demand sector is categorised into Residential, Non-Residential and Industrial sectors. The residential sector refers to the household sector, while non-residential

refers to the commercial sector which is less energy-intensive. The mines, textile factories, and other energy-intensive manufacturing sector make up the Industrial sector. The industrial sector consumes as greater chunk of electricity (>50%), followed by the household sector, with the commercial sector consuming the least figure 3.

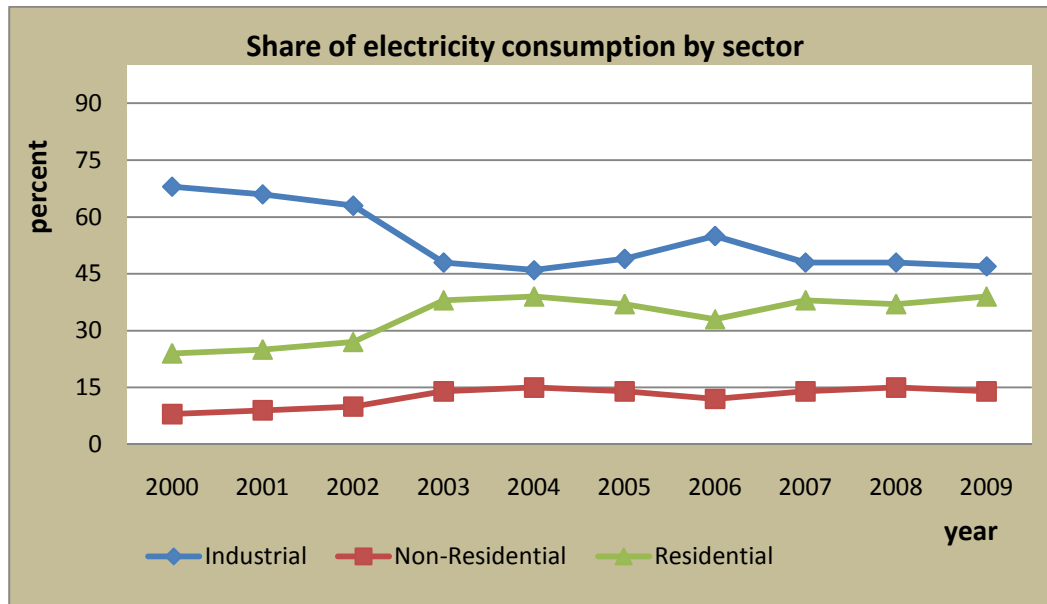


Figure 3 share of electricity consumption by sector (%)

Source: Adopted from Energy Statistics 2000-2009, Ghana Energy Commission

Of the industrial sector, the Volta Aluminium Company (VALCO) is a major consumer of power. In 2000 VALCO consumed 36% of total electricity figure 4; without VALCO in 2004 the residential sector (the household) consumed more that 50% of total electricity figure 4.

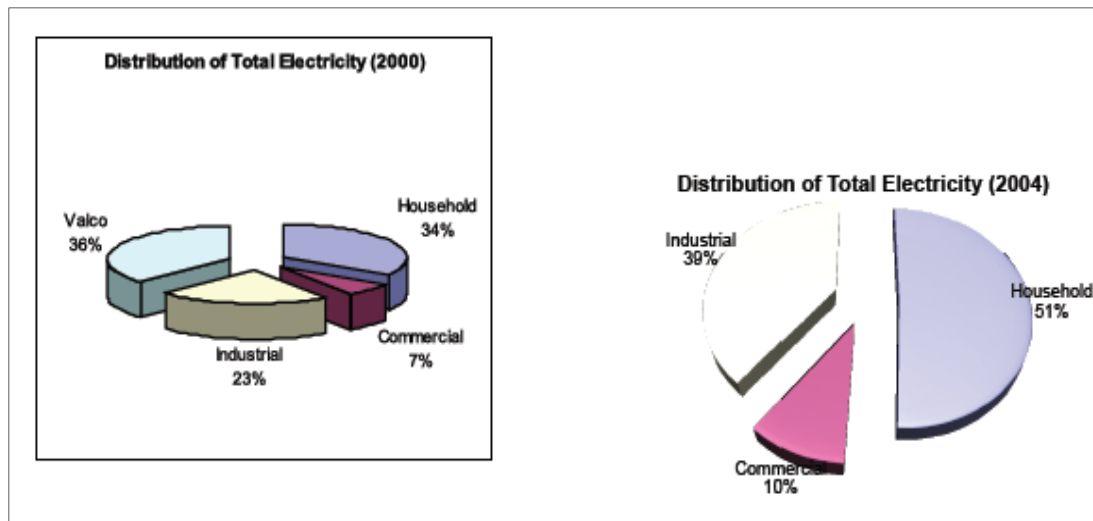


Figure 4 The impact of VALCO

Source: Energy Statistics 2000-2004, Ghana Energy Commission

Energy Crisis

In the latter part of 2006, Ghana was plunged into a state that has been described as energy crisis. This was as a result of inadequate power supply from the Utility caused by shortage of dam-water to run the nation's main energy source—hydro power. During the period the utility had no option but to resort to a scheduled load management system where the inadequate power was rationed nationwide. The effect on the various sectors of the economy was unpleasant. The Centre for Policy Analysis (CEPA)⁹, in reviewing the aftermath of the energy crisis brought to the fore the untold impact the energy crisis had on society and the economy. Local manufacturing costs escalated as a result of companies having to spend huge sums of money on fuel for generating their own power. This led to many companies cutting down on production, increasing amounts of importation of cheaper alternative products, downsizing among companies to mention but a few. It was reported that:

*"...about 33 companies filed for insolvency between September 2006 and March 2007 and over 2,300 workers have lost their jobs."*¹⁰

Government was not spared the brunt of the energy crisis. The Commissioner of Internal Revenue Service is reported to have expressed concern that:

"The power rationing programme made the Internal Revenue Service (IRS) to loose revenue estimated at 140 billion cedis which it could have collected as taxes for government [in

⁹ "The Centre for Policy Analysis (CEPA) is an independent, non-governmental think-tank, which provides rigorous analysis and perspectives on economic policy issues"

¹⁰ See <http://news.bbc.co.uk/2/hi/africa/6692605.stm>. BBC Investigating Ghana's energy crisis

2006]. *This was because the exercise made many companies in the country to record low earnings which could be taxed by the IRS.*¹¹

¹¹ See story on <http://mobile.ghanaweb.com/wap/article.php?ID=119361>, was sighted April 15, 2011

2. DATA

Data for the model is obtained from both national and international sources. International data sources include the International Monetary Fund (IMF), World Bank's World Development Indicators database, International Energy Agency (IEA), Energy Information Administration (EIA). Data sources assessed nationally were from the Volta River Authority (VRA), and Ghana Energy Commission (EC). The main source of data for gross domestic product is the IMF's World Economic Outlook database, of October 2009 because of its ease of access electronically; the other sources are used as supplements. Data on electricity capacity is obtained from the EC and supplemented by that from VRA, while data on peak electricity demand is mainly from VRA.

3. DYNAMIC PROBLEM

Hydro energy and Thermal energy are the main sources of electricity in Ghana, with total installed electricity capacity of 1730MW¹² as at 2007. This is made up of 1180MW of hydropower, and 550MW thermal power. Since the commissioning of the first hydro dam in 1966, Successive governments have made efforts in increasing the hydro generating capacities through either the construction of additional dams or retrofitting, ostensibly to produce more power to meet the growing electricity demand over the years. The addition of thermal power, as an alternative source of electricity, onto the grid began around 1993, and increased marginally to 550Mw by end of 2006.

These power sources do not seem to be adequate enough in the face of the nation's efforts to expand the economy through the drive to achieve some, if not all, of the millennium development goals, of which the achievement of some require full employment for all employable persons and full electrification.

It goes without saying that Population is increasing and doing so at a rate of 2.7percent per annum; and economic growth is spiralling up at an average rate of 5% per annum; both of which are indicators of increasing demand for electricity in the near future.

Figure 5 shows the trajectory of total installed electricity capacity (from 1990 to date) as well as for hydro and thermal capacities.

¹² A 400MW capacity hydrodam (called Bui Dam) is under construction and it is expected to be completed by end of 2010. Two hydro Dams make up the existing 1180MW hydro capacity, of which 1020MW is produced by the Akosombo Generating Station and 160MW produced by the Kpong Generating Station.

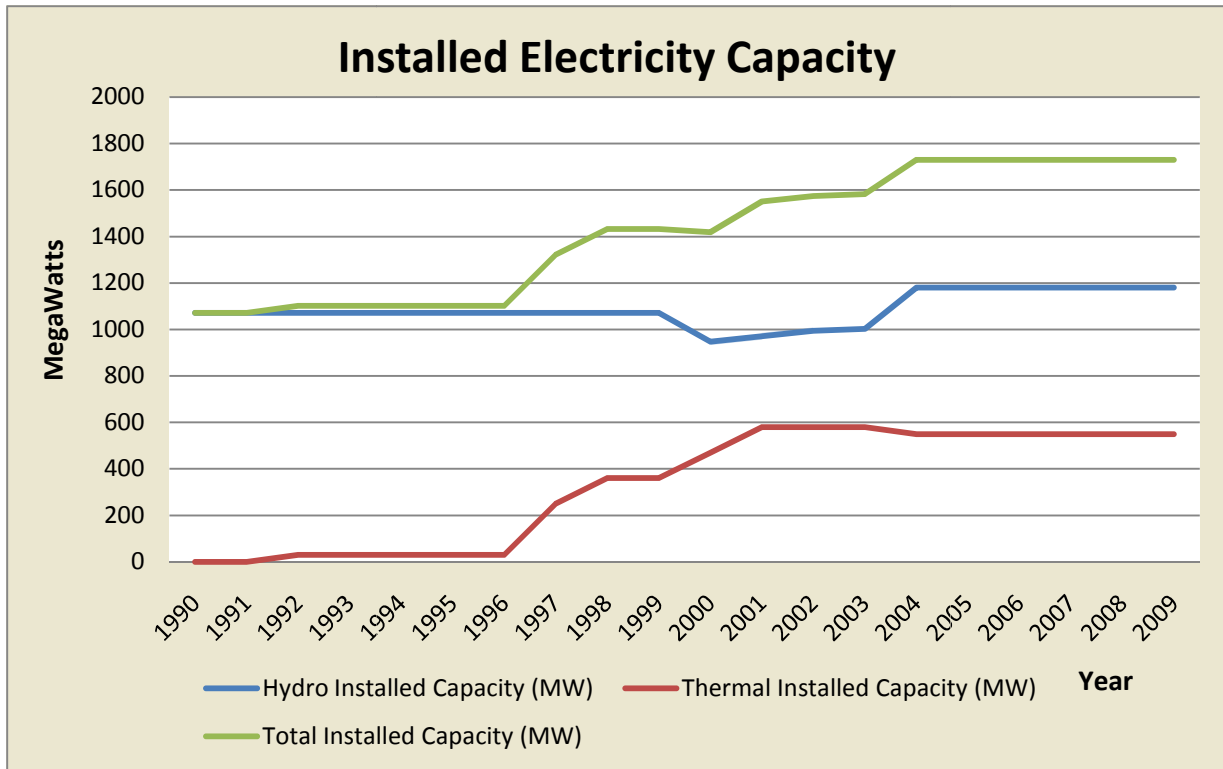


Figure 5: Installed electricity capacity

Source: Ghana Energy Commission

On the average, as depicted in figure 5, total electricity installed capacity has increased no more than 7% since 1990, with hydro constituting a substantial chunk of total capacity. Investment in thermal capacity only saw a somewhat significant increase in 1996 from a near zero to 550MW in 2001 to augment the country’s power-generating capacity.

In recent times, however, the highest annual GDP growth rate that the current level of electricity capacity has been able to support is less than 10% (World Bank, 2009) figure 6. It is important that we put the GDP growth rate in context here. First, we noticed that this level of growth was in an economy where there was not more than 50% electricity coverage in year 2000. The rural poor whose preoccupation is mainly agriculture—the mainstay of the economy—are the most affected. Electrification of the rural and the urban poor is still a challenge the nation is grappling with. Efforts to extend power to these areas began in the 1980’s with the institution of Rural Electrification Program (REP), but not much has been achieved. Several communities are still yet to be electrified.

There is therefore the potential of electricity demand rising far beyond the supply in the future. Karekezi’s remarks could not be disregarded in this instance, that: “*there are*

indications that macroeconomic reforms are generating rising incomes in the rural areas of Africa that could potentially translate to increases in the effective demand for modern energy services” (Karekezi 2002). Impliedly, growth in GDP figure 6 is indicative of increasing income levels, which eventually trickles down to the rural poor. Over the years, the agricultural sector has been a major sector of Ghana’s economy, contributing nearly 40%¹³ to GDP yearly.

Second, unemployment rate has increased from 4.7% of total labour force in 1992 to 10.4% in 2008 (WorldBank 2008). A decline in unemployment rate is a preferable move towards achieving the millennium development goal of full employment. Full employment would, sooner or later, take a toll on energy demand, both in the rural and urban regions of the country.

Third, we learn in November 2010 that Ghana attained a middle-income status with GDP revised from GhC 24.1 billion to GhC 44.8billion, after:

- a change in the base year from 1993 to 2006,
- improvements in the compilation methodology using 1993 accounting systems in place of the 1968 edition,
- improvements and revisions of data sources, and
- a classification update to International Standard Industrial Classification 4 (ISIC4) indicative of a growing economy¹⁴.

Without recourse to discussing specific economic indicators and the extent to which they have changed, we would like to take the aggregate GDP value as presented after the revision of the base year and make an assumption: that the Ghanaian economy is expanding. Concerns for energy demand are raised if this assumption holds true. Growth of GDP is undoubtedly linked to energy demand in general.

¹³ This is Based on Bank of Ghana Bulletin of August 2010. ie 37.6%, 37.2% and 38% for 2009, 2008, and 2007 respectively. Sighted April 21, 2011 at 14:00GMT+2. on <http://www.bog.gov.gh/index1.php?linkid=175&day=31&month=12&year=2010&stn=2003&fy=1>)

¹⁴ www.bizghana.com. After Rebased GDP, Still Many Open Questions, Article sighted November 9.,2010 at 12:40Gmt+2h

For the forgoing reasons, one could say that there is a potential problem of shortage of, and unreliable, power supply.

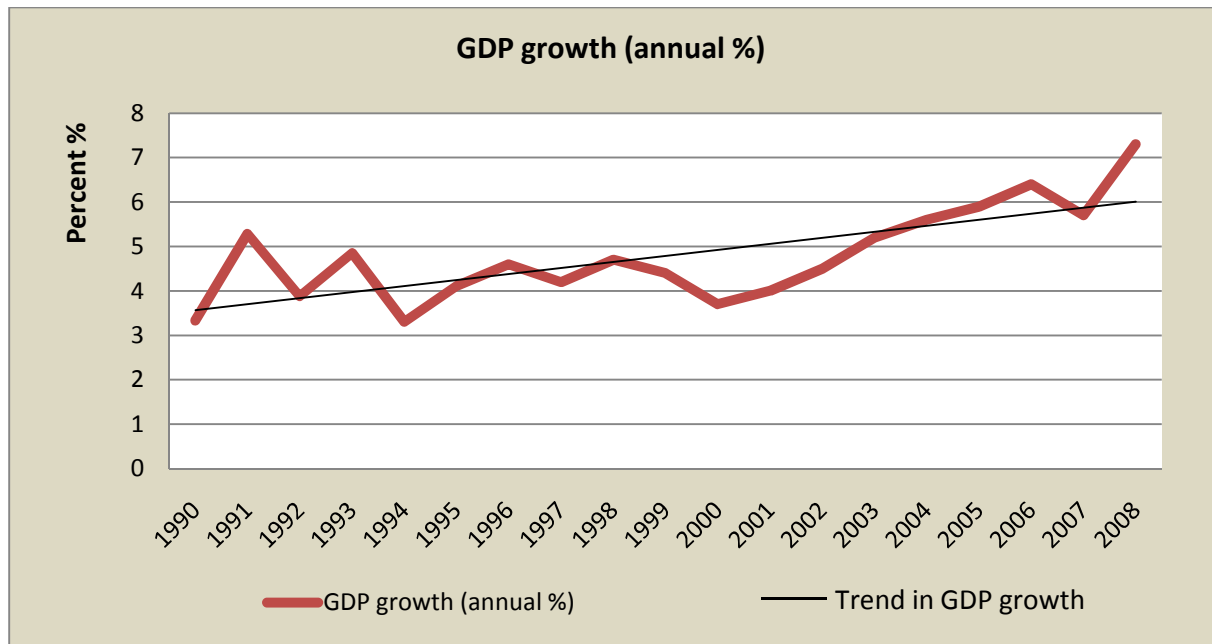


Figure 6: Annual GDP growth

Source: Adapted from World Bank’s World Development Index, 2008¹⁵

As regards energy production, figure 7 shows oscillating levels of electricity production between 1990 and 2004 peaking at 2001 with 7859.09 Gigawatt hours (gwh). The trajectory gives a possible indication that power production activities has not been without problems. The installed electricity capacity is not fully available for power generation throughout the year. Plants could be shut down for some months for maintenance work to be carried out, they could break down, and adverse weather conditions could also take a toll on them.

¹⁵This is calculated as the Annual percentage growth rate of GDP at market prices based on constant local currency. Aggregates are based on constant 2000 U.S. dollars. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Source: World Bank national accounts data, and OECD National Accounts data files.

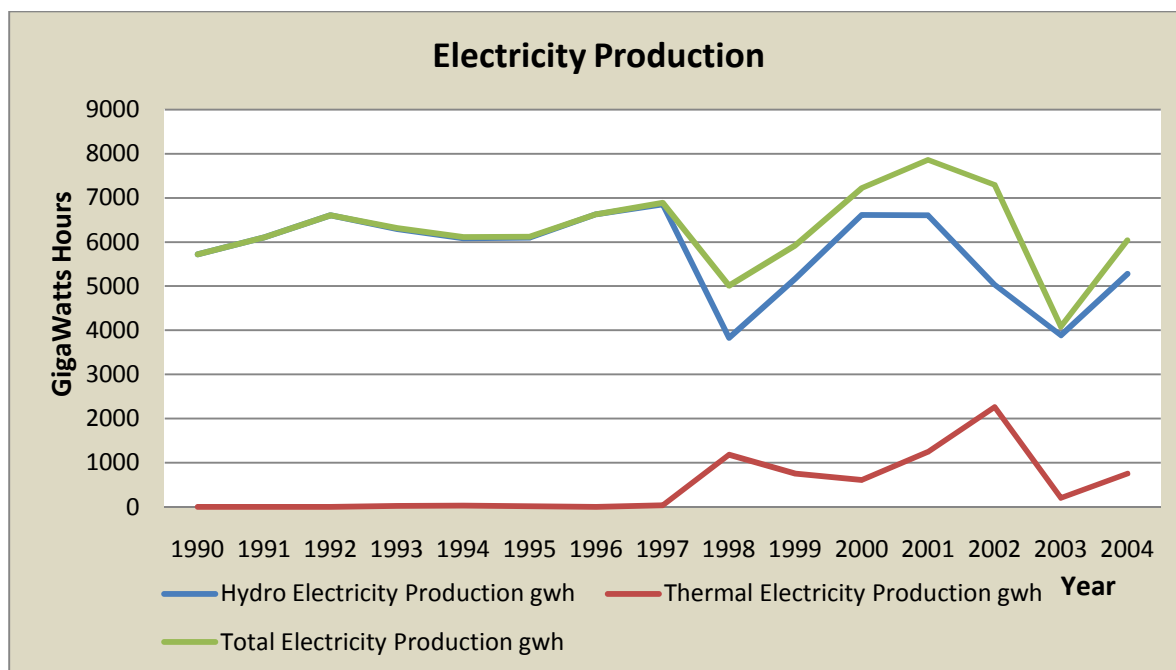


Figure 7: Electricity production

Source: Energy Commission, Ghana

Forth, let us consider the Capacity Margin with which the Utility has been operating over the years. Reference is made to the United States’ Capacity margin. Capacity Margin (also referred to as Reserve margin) as defined by EIA as the amount of unused available capability of an electric power system at peak load as a percentage of capacity resources.

While Capacity margin is seen as an indicator of system security of adequate supply, there is no standard margin to guarantee reliable, efficient supply. However a higher margin is preferable since it serves as a buffer to take care of unanticipated eruption of demand. Capacity margins for America’s utilities, America's utilities' averaged between 25 and 30 percent between 1978 and 1992¹⁶

Due to the rapidly growing economies of developing nations, and per EIA projections, electricity demand is expected to grow faster in developing countries than in developed countries. The reason for this is that “*electric power infrastructures in developed countries are relatively mature, national populations generally are expected to grow slowly or decline, and GDP growth is slower than in the developing nations*” (IEA, 2010).

¹⁶ See: http://www.eia.doe.gov/cneaf/electricity/page/fact_sheets/supply&demand.html

The rate of increase in US' electricity demand, for instance, averaged about 0.9% per year from 2000 to 2008, and expected to grow at about 1% per year through 2035 (IEA 2009). Developing countries, as the name connotes, are growing at a faster rate, with population on the rise. With such low growth rate in demand, a mature electricity market like that of the U.S need not necessarily keep higher reserve margin than a growing market should. Figure 8 shows actual and projected Capacity Margin of U.S' North American Electricity Reliability Corporation (NERC) between 1996 and 2004. The Capacity Margin between these periods average between 15% and 16% figure 8.

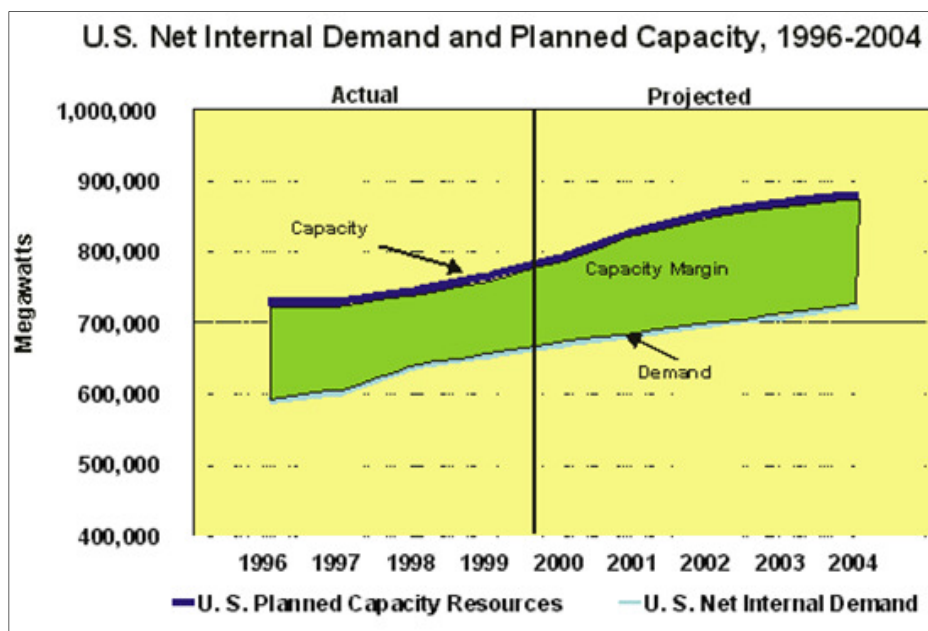


Figure 8: US Capacity Margin

Source: Adapted from Energy Information Administration, Department of Energy USA

Link: http://www.eia.doe.gov/cneaf/electricity/page/fact_sheets/supply&demand.html

It is also important to take a look at NERC's Planned Capacity Margins for the period extending beyond 2004 ending summer 2014. The average Actual and Planned Capacity Margins for the various Power Pools in US figure 9 shows an upward trend between 1998 and 2014, with the average increase in the Utilities' Capacity Margins above 20% by 2014. The trajectory labelled Contiguous U.S. averages the Capacity Margin of the entire North America region, see appendix I for values of the individual regional capacity margins. "Between 1978 and 1992, America's utilities' capacity margins averaged between 25 and 30

percent. Since 1992, the capacity margins have declined to less than 15 percent nationwide...the decline is expected to reverse...with planned capacity expected to grow".¹⁷

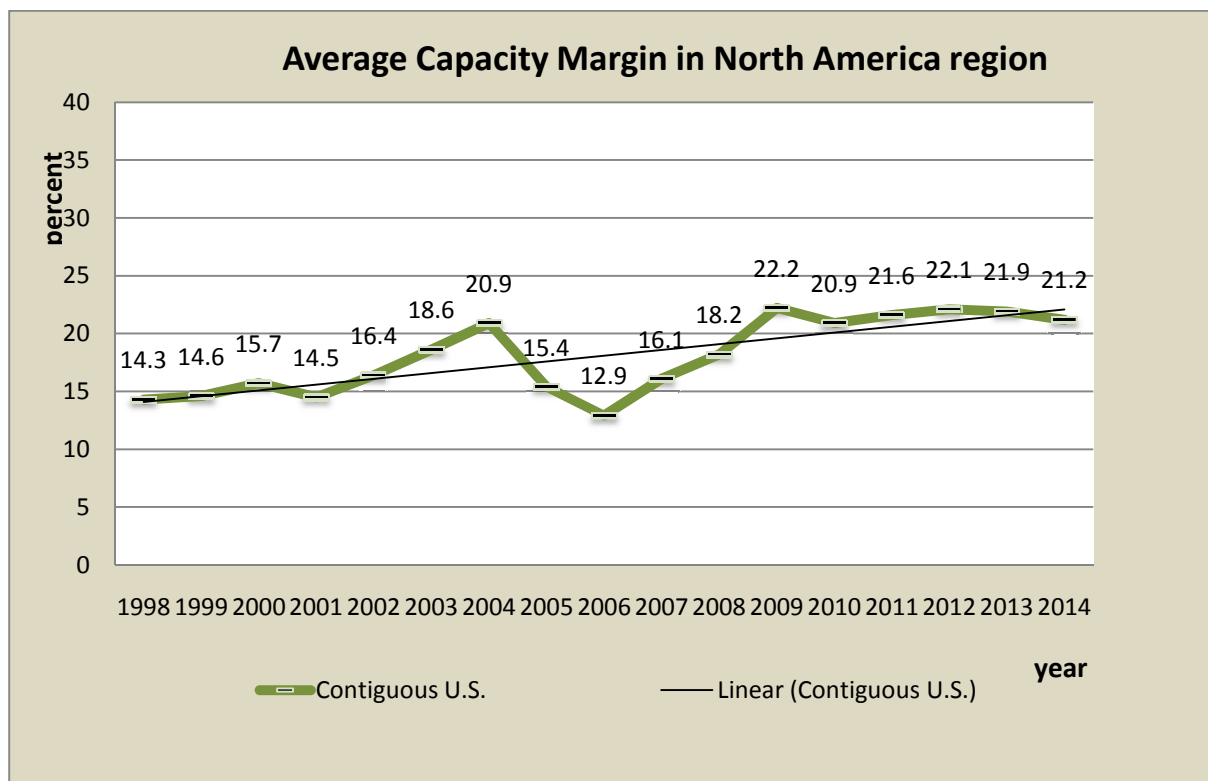


Figure 9: Trajectory of Average Capacity Margins (Actual and Planned) by North American Electricity Reliability Corporation (NERC), summer 1998 through 2014¹⁸

Source: Adapted from Energy Information Administration, Electric Power Annual 2009¹⁹

In pursuant of United Nation’s millennium development goal (MDG) number 1 of *having to eradicate extreme poverty and hunger*, the Government of Ghana is expected to pursue macroeconomic policies that would help stimulate growth. Target 1b of the MDG is to achieve full and productive employment and decent work for all, including women and young women, measurable, in part, with such indicators as:

- Growth rate of GDP per person employed

¹⁷ http://www.eia.doe.gov/cneaf/electricity/page/fact_sheets/supply&demand.html

¹⁸ The NERC entities include: **FRCC**-Florida Reliability Coordinating council, **MRO**-Midwest Reliability Organisation, **NPCC**-Northeast Power Coordinating council, **RFC**-Reliability First Corporation, **SERC**-SERC Reliability Corporation, **SPP**-Southwest Power Pool, **TRE**-Texas Regional Entity, **WECC** Western Electricity Coordinating Council

¹⁹ See for table: <http://www.eia.gov/cneaf/electricity/epa/epat4p3.html>

- Employment to population ratio

Industrialisation is imperative to create employment opportunities in order to achieve full productive employment. Poverty could be reduced through industrialisation. However, demand for modern energy services is more likely to rise with the establishment of institutions and industries that provide job opportunities. While these establishments are more likely to add onto industrial and commercial demand for energy, rising incomes of employees (especially the rural folks) could potentially translate into increases in demand for modern energy services such as electricity (Karekezi 2002). For instance, in year 2000, Ghana's main Aluminium Company, Volta Aluminium Company Ltd (VALCO) alone consumed 36% of total electricity, while the industrial sector consumed 23%, with the Household and the Commercial sectors consuming 34% and 7% respectively. Therefore, transforming the Ghanaian economy into an industrial one, possibly with the establishment of electricity-intensive manufacturing firms, would raise concern for energy. Sufficient and reliable electricity is therefore required.

As noted by Karekezi 1999, the inadequate electrification of rural areas, where in many cases the majority of the population resides, is more likely to account for the low levels of power consumption in many developing countries. Electricity consumption is therefore confined to the energy-intensive sub-sector of commercial and industrial enterprises, as well as high-income households (Karekezi, 1999). Between 1990 and 2007, electric power consumption per capita of Ghana has declined by about 18.8% (from 319.3584kwh to 259.4556kwh) (WorldBank 2008). What could account for this decline? It is possible that population has increased while electrification of communities stagnated or electricity consumption has declined due to economic reasons.

4. HYPOTHESIS

The working hypotheses are the following:

H₀: Sole reliance on hydropower in Ghana would not stifle economic growth

H₁: Sole reliance on hydropower would stifle economic growth.

H1₀: Sufficient electricity capacity does not help improve economic growth

H1₁: Sufficient electricity capacity helps improves economic growth

Research question

The research centres on the following thematic questions:

- How could the current state of electricity capacity impact on the achievement of millennium development goal 1: including universal access to electricity, and full employment?
- How does the inadequate power generating capacity limit the growth of the economy?

Following the dynamic problem description, and in line with the hypothesis statement above, the hypothesis is explained with both causal loop diagram and stock and flow diagram.

Causal Loop Diagram

In explaining the hypothesis we would first describe the structure that underlies the behaviour of the hydro sector. The negative feedback loop **CI** in figure 10 depicts growth in electricity generation capacity through investment, which is mostly initiated by government. Since investment in electricity capacity does not instantaneously translate into a full-fledged operating capacity, we represent this with a discrete first order delay with stock christened *capacity under construction*. This is so because capital investments are not continuously made in the power sector: one investment comes several years after the other. The two crossing lines on the arrow linking *capacity under construction* and *electricity generating capacity* are indicative of the waiting period between the two state variables. *Electricity*

generating capacity refers to the capacity of installed power plants. Until they become fully operational and added to the power grid, power plants are considered here to be under construction. The decision-making process is such that government compares the installed electricity generating capacity with its goal (*desired capacity*); the resultant discrepancy is addressed by government, taking steps to bring *electricity generating capacity* closer to its goal. If there is a discrepancy between electricity generating capacity and desired capacity, investment is initiated to bring electricity generating capacity close to the set goal.

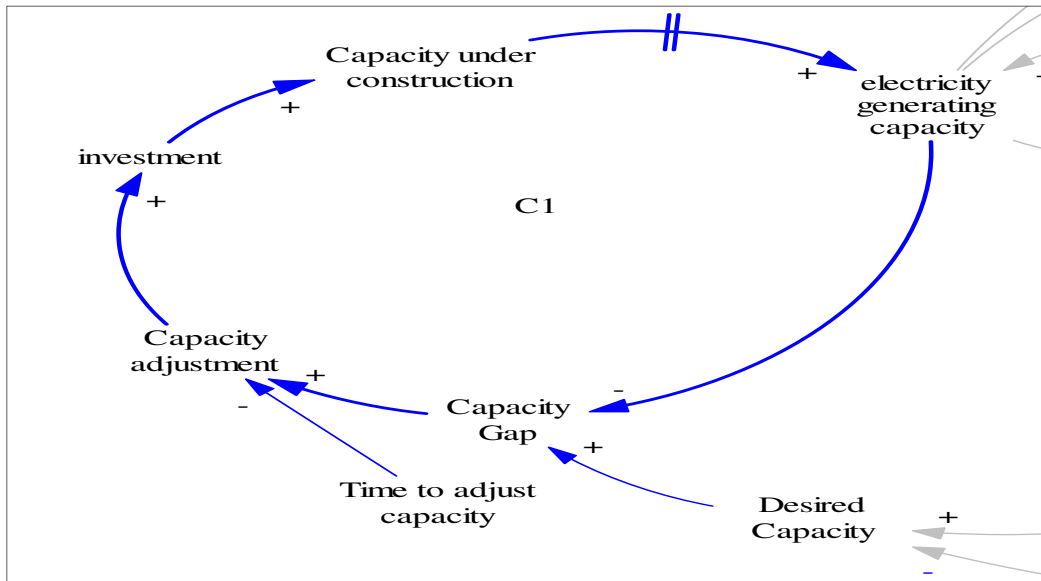


Figure 10: Loop C1, capacity investment

The decision process in figure 10 is in line with the feedback process involved in any decision-making setting. The Utility obtains information about their system and that information feeds back into their decision in making changes to their system. Figure 11 shows the generic structure and behaviour in any decision-making and feedback process and it (figure 10) has some resemblance with figure 11.

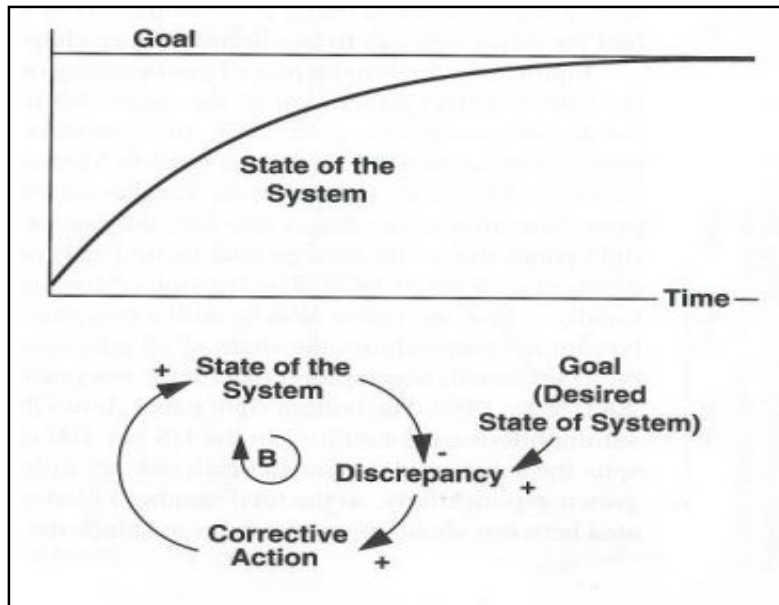


Figure 11 Goal seeking: Structure and Behaviour

Source: Sterman (2000, p.111)

But what influences decisions on the amount of power capacity that should be desired? Figure 12 shows how the goal for power capacity is determined. We hypothesised that this decision is based on two major factors: demographical changes and production activities. These are represented by *Population* growth and economic growth (Gross Domestic Product—hereafter referred to as *GDP*). Population and GDP are, therefore, the main drivers of electricity production. While in the urban areas it is relatively easy for the population to get connected to electricity grid, the rural areas depend on the state to extend electricity networks to their areas before they could have access to electricity. In both cases increase in population will lead to increase in electricity usage, holding all other things constant. A boost in economic activities, on the other hand, will result in increase in electricity usage; hence electricity consumption will surge eventually, *ceteris paribus*. Therefore *Desired Production*, which refers to the amount of electricity that have to be produced based on pressure from the population and economic activities, increases along with *Population* and *GDP*. Similarly, *Desired Capacity* figure 12 which refers to the needed electricity capacity at a given period, changes as population and the economy's needs for electricity change. Desired capacity is therefore dictated by changes in *Population* and *GDP*.

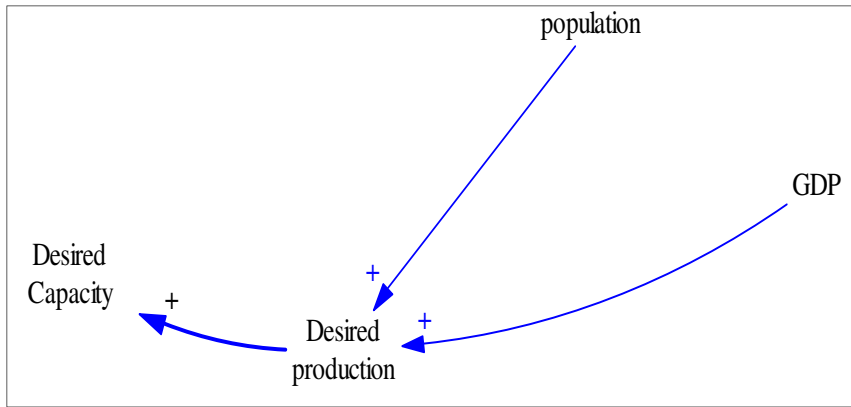


Figure 12: Desired Production and capacity

As it were, depreciation which is the measure of the wear and tear of installed capacity, affects the functioning of generation capability negatively. As capacity increases, depreciation increases proportionately. Increases in depreciation in turn reduce the outputs of capacity. Loop C2 in figure 13, apparently reduces the functionality of the generating capacity. As accounting concepts dictate, depreciation involves spreading out the cost of asset over its useful life, in order to account for the costs associated with such factors as wear and tear of machine parts. But *replacement investment and maintenance* are carried out in order to reduce the effects of depreciation and tend to keep constant the outputs of power generation capacity. This periodic investment in maintenance and replacement activities helps to keep the power plants in good shape, loop R2 figure 13. Retrofitting work, sometimes, is carried out on power plants to restore them to their original state. After retrofitting, plants generally become more efficient and their outputs exceed that which they originally produce, due to technological improvement. As discussed earlier, after retrofitting the Akosombo hydropower plant it gained a significant 108MW in addition to its original 912MW; a gain that was almost 12% due to technological improvement.

Hydro generating plants and machinery have an average lifetime 33-45years²⁰, at the end of which plants are either replaced or retrofitted.

²⁰ Source: Volta River Authority

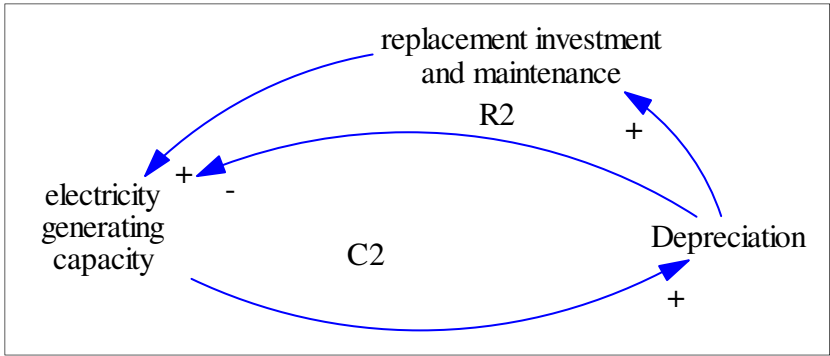


Figure 13: capacity replacement

From figure 14 *Total Electricity demand*, the total demand from the economy is met with electricity supply (*potential electricity production*) from total installed power plants (*electricity generating capacity*). *Total electricity demand* is thus influenced by *Population* and *GDP* as discussed earlier. The reinforcing feedback loop *R1* in figure 14 indicates that more electricity usage improves GDP, whilst improvement in GDP also results in more electricity usage. There is a bi-directional relationship between energy usage and economic growth (Akinlo 2008); (Wolde-Rufael 2009). Electricity undoubtedly is a form of energy, and is christened as a modern form of energy. This formulation is in line with the theory that energy plays an important role in the production process of both goods and services.

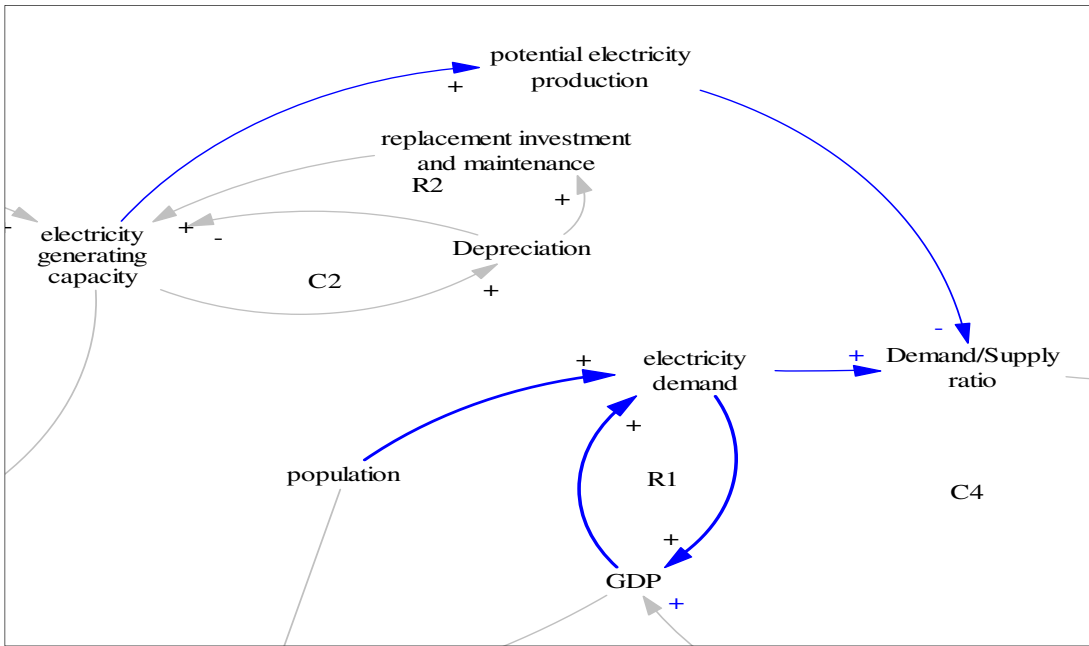


Figure 14: electricity demand

The interaction between demand and supply creates the need for either more capacity to be provided or the status-quo to be maintained. The effect of loop R1 figure 15 is counteracted by loop C4, in that when electricity demand increases as a result of population growth and gdp (loop R1), all other things remaining constant, demand will exceed supply which then limits *capacity availability* through the use up of *Capacity margin*. Electricity demand will thus slow down because of limited capacity and GDP growth is suppressed. No real quantity can grow forever Sterman (2000, p. 285).

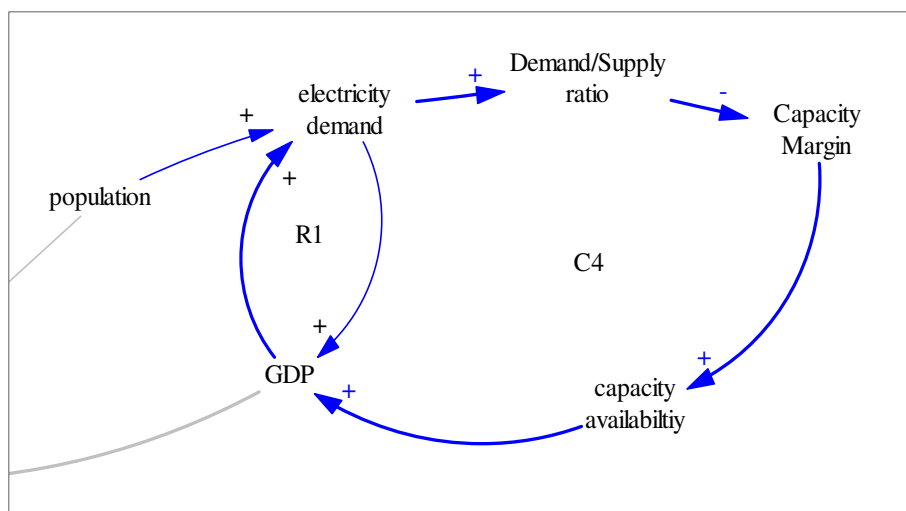


Figure 15: Demand and Capacity margin

On the other hand, reductions in capacity availability as a result of increasing demand leading to reductions in Capacity Margin raise concern for the Utility to adjust its electricity generation capacity upwards through investment. Loop C3 figure 16 becomes dominant to restore the imbalance between demand and supply (*Demand/Supply ratio*). Holding electricity demand constant an increase in electricity supply will decrease *Demand/Supply ratio*, hence Capacity margin rises. This development will lead to more capacity being made available, a case in which the Utility desire to reduce its production capacity.

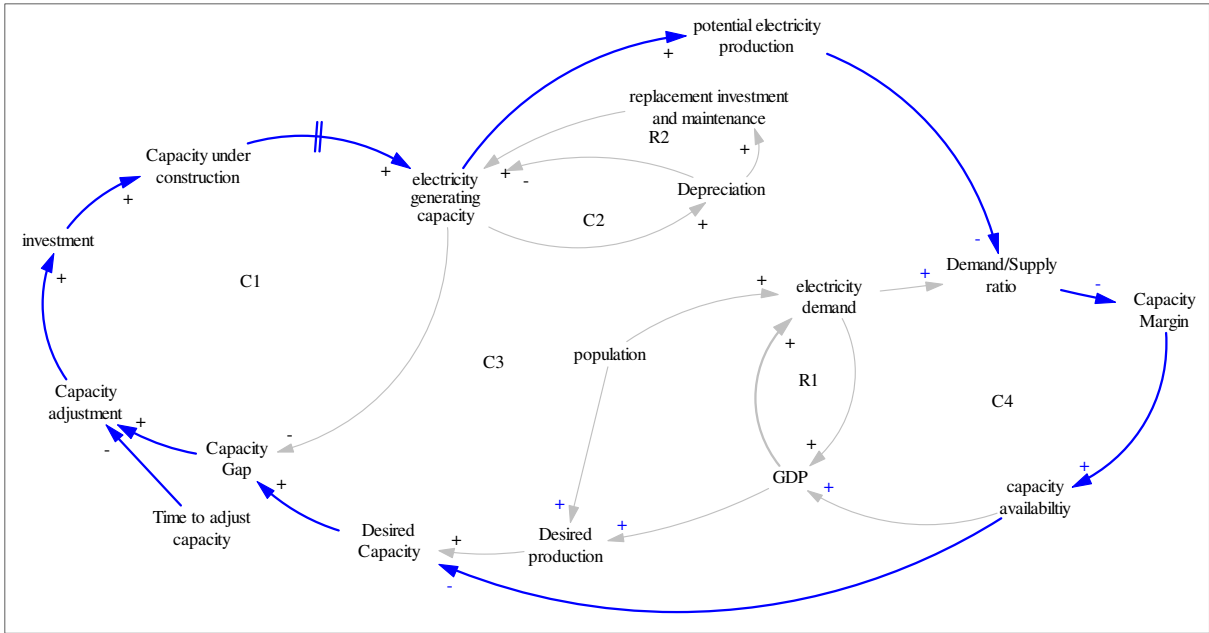


Figure 16: Supply and capacity margin

Capacity Margin is expressed mathematically per the definition by Energy Information Administration as:

$$\frac{(\text{Supply Capacity} - \text{Demand})}{\text{Supply Capacity}}$$

This can be rewritten as:

$$1 - (\text{Demand/Supply Capacity})$$

Hence capacity margin is the excess of ONE over demand/supply ratio.

Reinforcing Loop R3 (figure 17) dampens electricity consumption through increases in prices. When electricity demand decreases, capacity margin relatively raises leading to increased operating cost because of fixed operating costs associated with the unused capacity. Operating cost relatively rises and the Utility will eventually transfer the increases to the consumers in the form of price. Increases in electricity prices slow down electricity consumption.

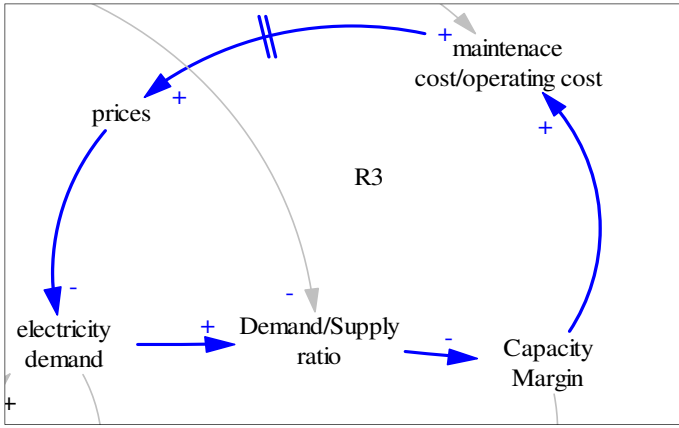


Figure 17: Price effect on demand

Figure 18 is the summary of the hypothesis in the form of Causal Loop Diagram.

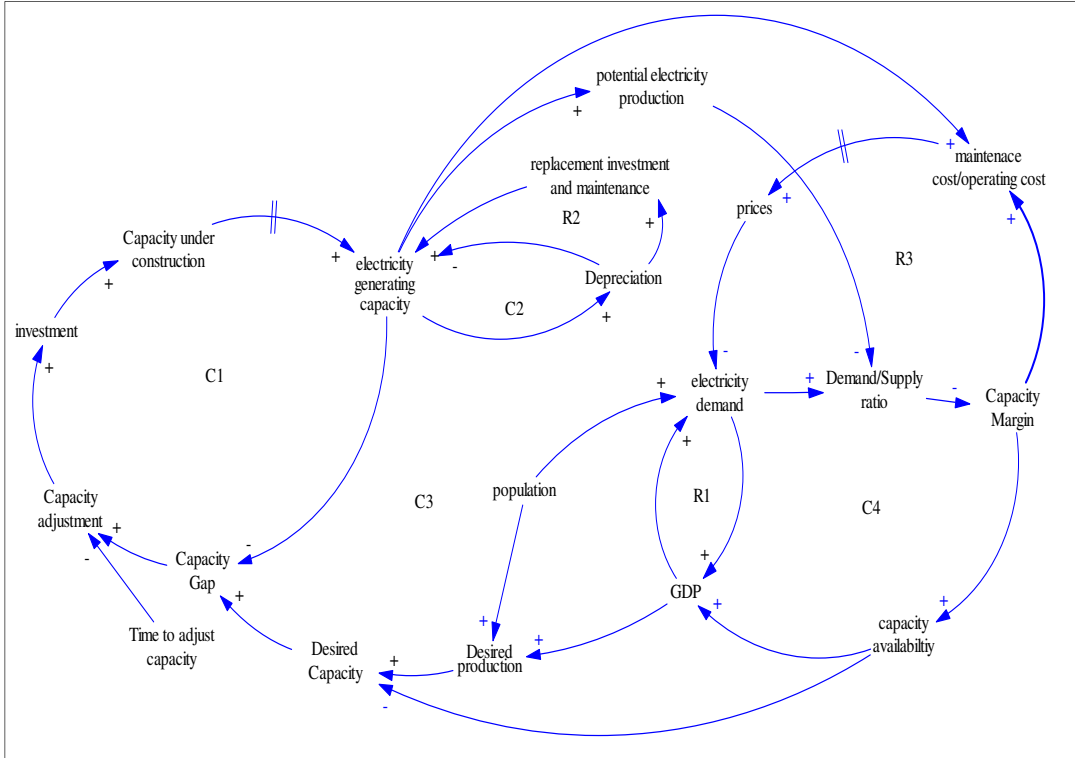


Figure 18: Summary of Causal Loop Diagram

Model Description

In this section we explain our hypothesis with Stocks and Flow Diagrams. *“Stocks are accumulations, which characterise a state of the system and generate the information upon which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow” (Sterman 2000 p.192).*

Assumptions:

The assumptions based on which the model is developed and simulated are as follows:

- Transmission and Distribution losses are within acceptable levels as spelt out by the Public Utilities and Regulatory Commission (PURC).
- All hydropower potentials are exhausted by 2011 upon completion of the 400MW Bui Dam, and the Bui is operational and connected to the grid by 2011²¹.
- The Private sector is willing, and has adequate capital, to invest in power generation plants immediately government permits them by law.
- Macroeconomic policies and conditions remain unchanged throughout our simulation period
- Demand for electricity refers to local demand within the Ghanaian economy, and excludes demand from outside the borders of Ghana.

Model boundary

Before we begin our test we would like to define our model boundary: the time frame for our simulation. Our simulation begins in 1990 and ends in 2015. We choose 1990 because from 1990 to date a number of events have occurred that has impacted not only the electricity mix in the country, but also the transmission and distribution structures as well as regulatory control of this sector. The power sector over this period has seen a lot of reforms. The year 2015 marks a year of achievement of many of United Nation’s Millennium Development goals including universal access to energy and full employment. Achievement of these goals will have great impact on gross domestic product as well as electricity consumption. The

²¹ Though some media reports indicate that the Bui dam will be commissioned in December 2012 see <http://news.myjoyonline.com/politics/201102/60967.asp> sighted March 15 2011.

model boundary chart (table 4) spells out the scope of our boundary, indicating the exogenous, endogenous and excluded variables.

Exogenous variables	Endogenous variables	Excluded variables
Population	Per capita GDP	Transmission Capacity
Gross Domestic Product (GDP)	Estimated maximum demand	Transmission losses
	Capacity Margin	Distribution losses
	Goal for hydro sector	cost of construction
	Goal for rops sector	Planned retrofit and/or replacement for rops power plants
	Investment rate in ROPs	Emission from power plants

Table 4: Boundary Chart

The model is separated into four interconnected sectors, namely *Hydro sector*, *Demand/Supply sector*, *Rest of Power Sector (Rops)* and *Cost and Price Sector*. The structures in each sector that underlie the behaviour of the power system are described here:

The Hydro sector

The hydro sector illustrates the structure that generates the behaviour of the hydro plants. The main stock in this sector is *Hydro capacity installed* (figure 19) which refers to the total generation capacity of the hydro plants in Ghana. Measurement unit for this capacity is Mega Watts (mw). Since stock are accumulations, which characterise the state of systems and generate the information upon which decisions and actions are based (Sterman, 2000 p.192), we conceptualise *Hydro capacity installed* as an accumulation of generators' and turbines' capacities. Hydro installed capacity changes upon the installation of hydro plants and deterioration of same.

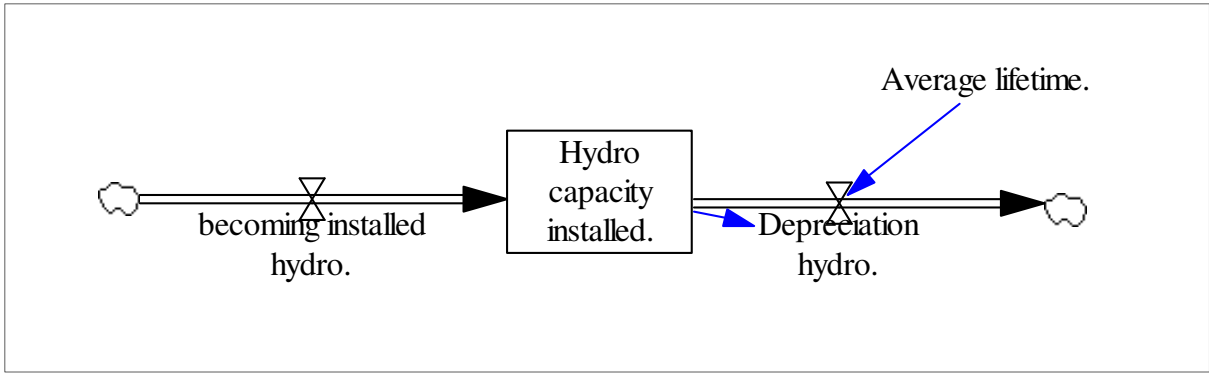


Figure 19: Hydro capacity

The state of hydro capacity changes after the completion of construction and the hydro plant is fully installed, and then connected to the national grid. *Becoming installed hydro* figure 20 represents the rate of transforming dams that have just undergone construction into a fully operational facility, while *depreciation* represent the yearly fraction of loss over the expected life of the dam plant and machinery, occurring as a result of wear and tear. However, we assume that periodic maintenance and repair works (*maintenance and replacement investments*) figure 20 carried out on hydro plants are enough to restore the amount of capacity lost through depreciation.

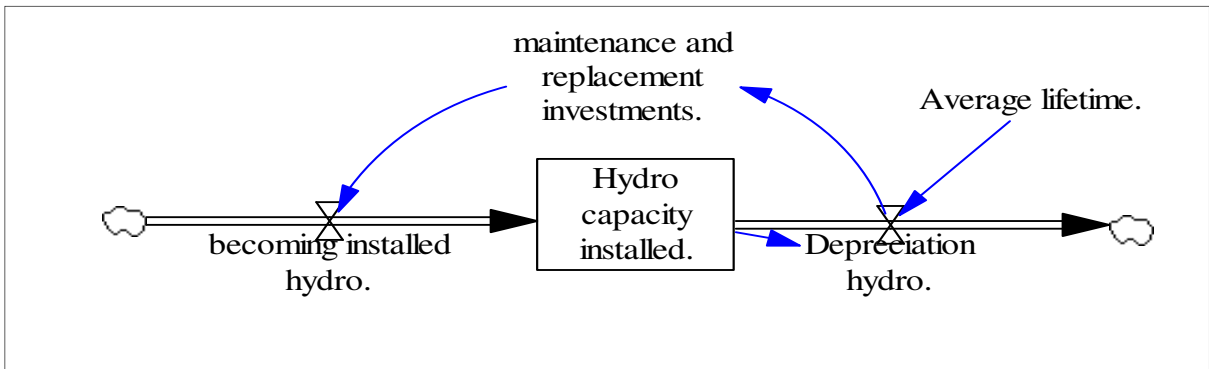


Figure 20: maintenance and replacement investment

In addition to depreciation which to a large extent is cancelled off by maintenance work, we also assume that every 30years hydro plants undergo retrofitting work, which will result in the plants becoming more efficient due to technological changes; and that hydro plants are more likely to gain some more capacity after undergoing retrofitting work. *Potential boost through upgrade* (figure 21) adds capacity gained through retrofitting back to the stock of

Hydro capacity installed. In our model *Potential boost through upgrade* adds ten percent (0.1)²² of the total installed hydro capacity to the stock in year 2001. The variable *upgrade fraction* is the potential rate of increase in plant output attributable to technological improvement in new plant parts used for retrofitting. It is chosen to be 0.1. *Upgrade time* is a pulse time that allows upgrade to recur at a regular time period which starts from year 2001.

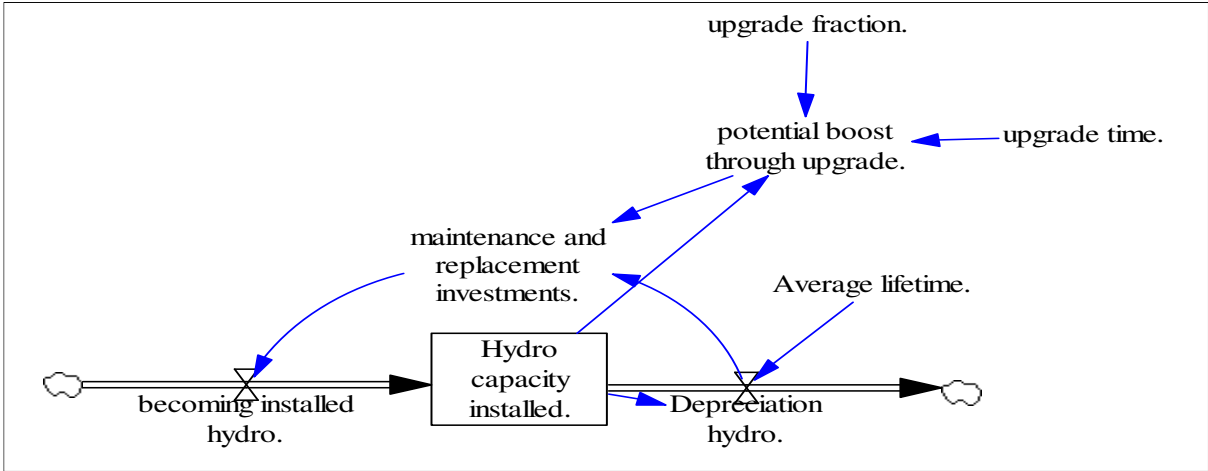


Figure 21: retrofitting

Having described how the stock of installed hydro capacity changes, we now take a step back to consider how other variables cause these changes to happen. Through investment construction of hydropower begins. The progress of construction work is conceptualised as an accumulation and is represented by *Hydro capacity under construction* figure 22. Upon completion of construction work and the lapse of construction time (*average installation time*), capacity is considered to be fully installed. This completed capacity now moves into the stock of hydro capacity through the flow, *becoming installed hydro*.

²² “At the full completion of the Retrofit Project (Akosombo hydro dam), the generation capacity increased significantly by 108mw, from 912mw to 1020” Source VRA. The gain in capacity is approximately 10%.

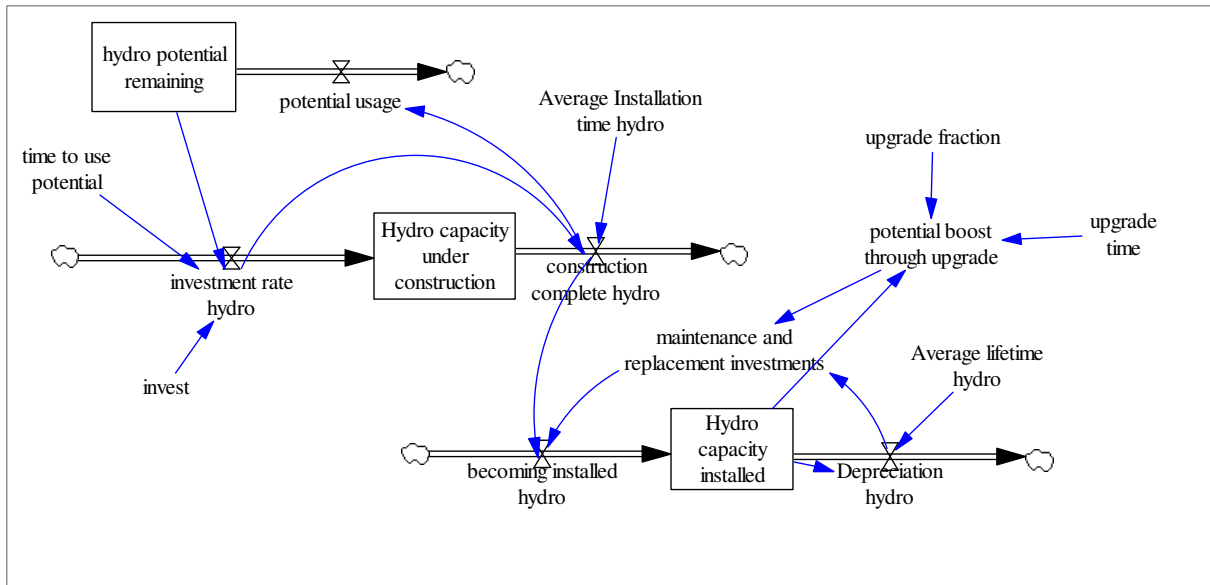


Figure 22: Potential hydro capacity and capacity under construction

The limiting factor here is the stock of *hydro potential remaining*. This stock represents the total hydro potential that is yet to be tapped. Investments in hydro capacity cannot be made beyond this natural hydro-resource capacity.

However, we again assume that before hydropower investments are made, the Utilities would compare the capacity they desire with the existing (*capacity gap*) and invest in plant capacity that will bring *hydro capacity installed* close to their *desired capacity* figure 23. Investment is based on the extent of gap between the goal and the existing stock. Bigger gap will require making huge investments in power plants in order to close the gap. Since the realisation of capacity gap and making of investments to close the gap do not happen at the same time, we represent this lead time with a delay function. Our model shows that hydropower investments are drawn from the stock of *hydro potential remaining* because hydro investments cannot practically exceed the potentials of natural conditions available.

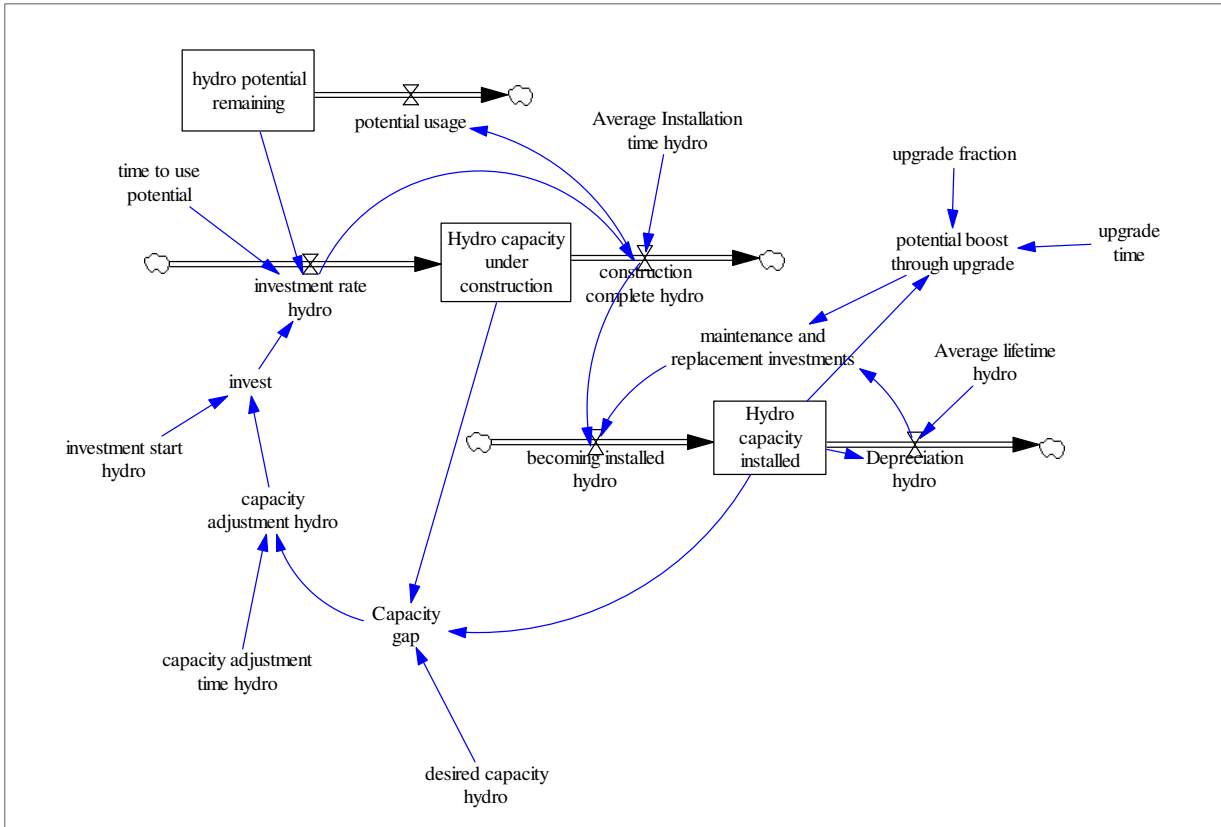


Figure 23: Hydro capacity gap

In deciding on desired capacity for the Utilities it is assumed that desired capacity is influenced by the size of population and their need for power, as well as changes in economic activities as discussed earlier. Since “Goals are often partially affected by past performance and partly by various external factors” (Sterman, 2000 p.534), we represented *desired capacity hydro* in our model figure 24 as a weighted average between *stated goal hydro* and *desired hydro production*. Desired hydro production represents the amount of capacity needed in order to satisfy the growing demand for the utility’s ‘product’. This decision is influenced both by, as Sterman puts it, past performance (which is internal) and external factors. The internal factors could include the technical conditions that impact the efficiency of the operating capacity installed. The Utility will customarily desire to have optimal performance from their installed capacity, and would therefore set their short-term goal to be the optimum performance from existing capacity. Fetching information on installed capacity past performance takes some time: this lead time (between collecting and analysing these pieces of information) is represented in our model with a first order information delay function, with delay time of one-quarter of a year.

The external factors considered are population and economic growth. In our model economic and population growth are used in estimating *perceived maximum demand*. The minimum of *perceived performance of installed capacity hydro* and *perceived maximum demand* define *desired hydro production* figure 24. This means that if maximum demand is less than the Utility's maximum supply, then the Utility will produce exactly what is demanded. But if maximum demand exceeds the Utility's supply, then the Utility will supply power by operating at full capacity. In the latter case the desired production will equal *perceived performance of installed capacity hydro*. Then again, we posit that higher growth rates in the external factors will mean higher demand for electricity. Therefore we conceptualise that increasing levels of *perceived maximum demand* will have a greater effect on *weight of stated goal*. The maximum value for *weight of stated goal* is one (1), which indicates full weight on *stated goal hydro*; and minimum value is zero (0) which indicates no weight at all on *stated goal hydro*. At full weight the stock of *hydro installed capacity* seeks *stated goal hydro*. When the weight is 0.5, for example, the stock seeks 50% of *stated goal hydro*, and 50% of *desired hydro production*. However, if the weight is zero, the system maintains the status-quo.

But this decision should be made with regard to the limit set by natural conditions (*hydro potential remaining*). The natural condition that sets the boundary for hydropower capacity is the availability of water bodies.

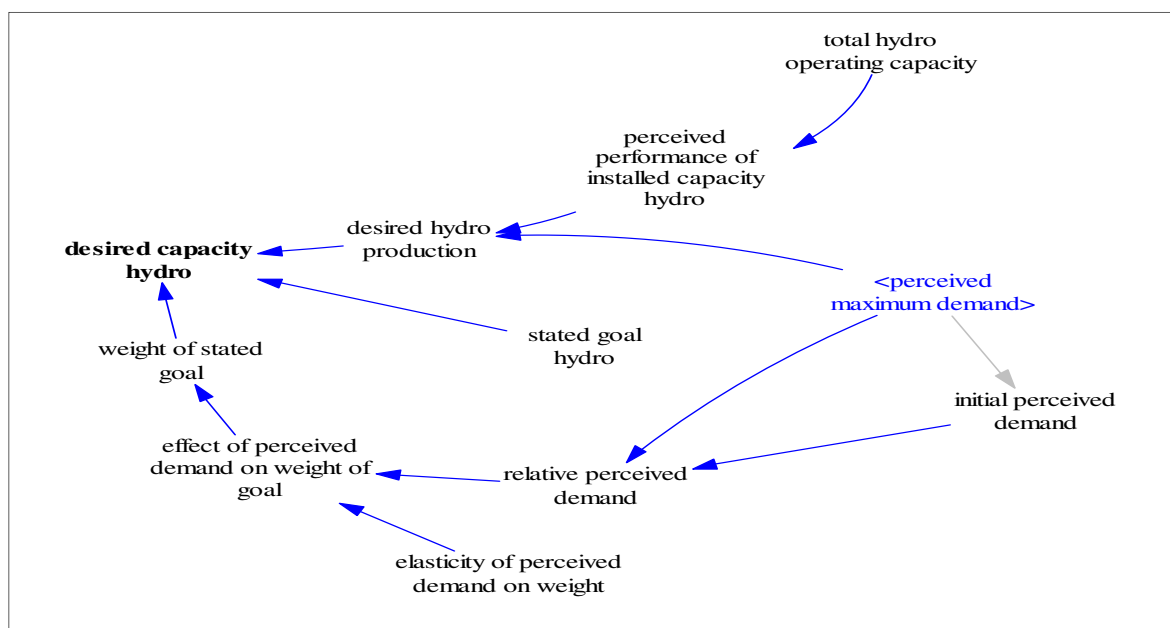


Figure 24: Desired capacity hydro

Whenever there are changes to the goal, *installed capacity hydro* therefore adjusts to the new goal (*stated goal hydro*) figure 25. But where do the conditions that trigger the change in stated goal hydro come from? We posit that stated hydro goal changes inversely with *capacity availability ratio*, which is a function of *Capacity margin*. *Capacity availability ratio* is a fraction of *capacity margin* and *reference capacity margin*. As defined earlier, *Capacity margin* is the excess of operating capacity over perceived maximum demand taken as a fraction of operating capacity. We set a target margin referred to in our model as *reference capacity margin* so that when the target is approached then there is to raise *stated goal hydro* in order to form the basis for initiating investments in hydro plants.

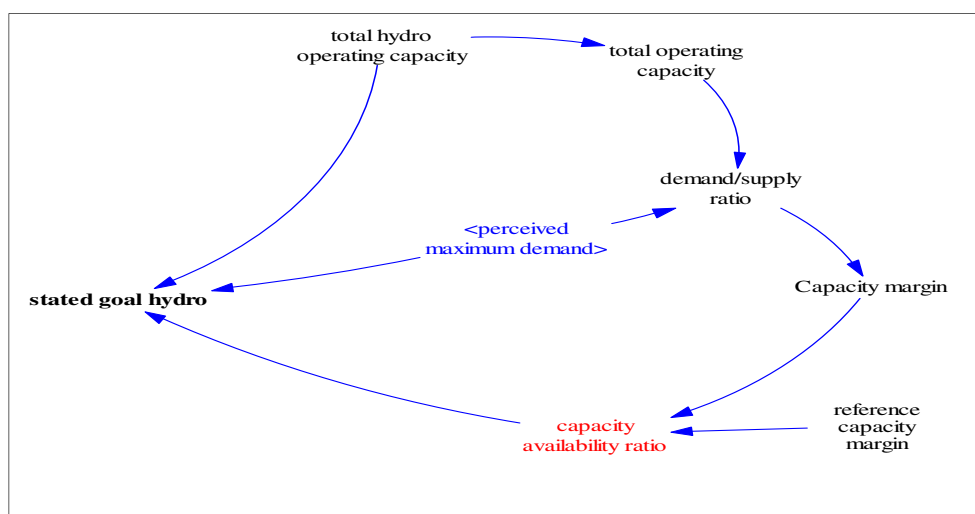


Figure 25: stated goal hydro

Rest of power sector (Rops)

This sector aggregates all power generation capacity and power potentials other than hydro. These may include gas-fired, oil-fired, coal-fired power plants, wind turbines, waste-to-energy, and solar sources which could supplement the hydro. *Installed capacity rops* figure 26 used in this sector refers to capacities of power plants other than hydro. This sector is not structurally different from the hydro sector, such that the same decision rules used in formulating the hydro sector apply here as well. However, this sector excludes retrofitting. We assume that thermal power plants retrofitted will have their output capacities unchanged.

Like the hydro sector, the stock of *installed capacity rops*, changes with changes in its flows. *Maintenance and replacement investments rops* keep the stock stable over time, as depreciation ‘eats away’ its output.

The capacity desired for this sector (*desired capacity rops*) is the capacity needed in addition to hydro capacity in order to close the gap between demand and supply. We develop this sector as a discrete model, with *simulation start* defining the discrete period for investments to be made. Investments in this sector are made out the stock of *potential capacity rops*, which sets the limit for investment. Like the hydro sector, when all the rops potential is exhausted no investment can be made. There is currently limited private participation in this sector in Ghana; hence we assume that price increases will serve as a form of motivation to increase their plant capacity.

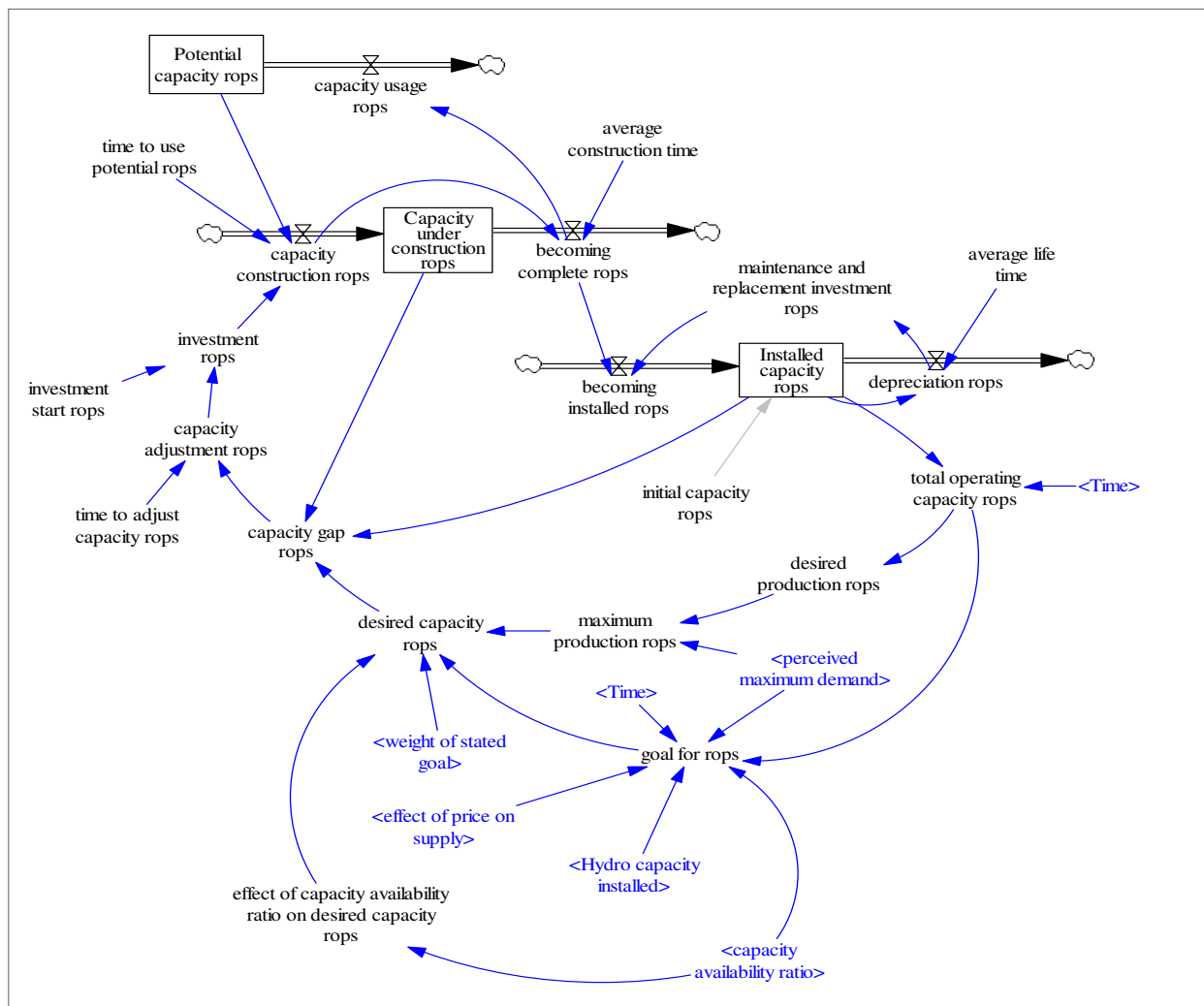


Figure 26: Rest of power sector

Demand/supply sector

In this sector we hypothesised how electricity demand is estimated. This estimated demand is derived mainly from changes in population and economic activities. In so doing, we split electricity demand into two main categories: *domestic demand* on one hand, and *industrial and commercial* demand on the other. *Initial peak demand* figure 27 represents the maximum peak demand/generation in 1990.

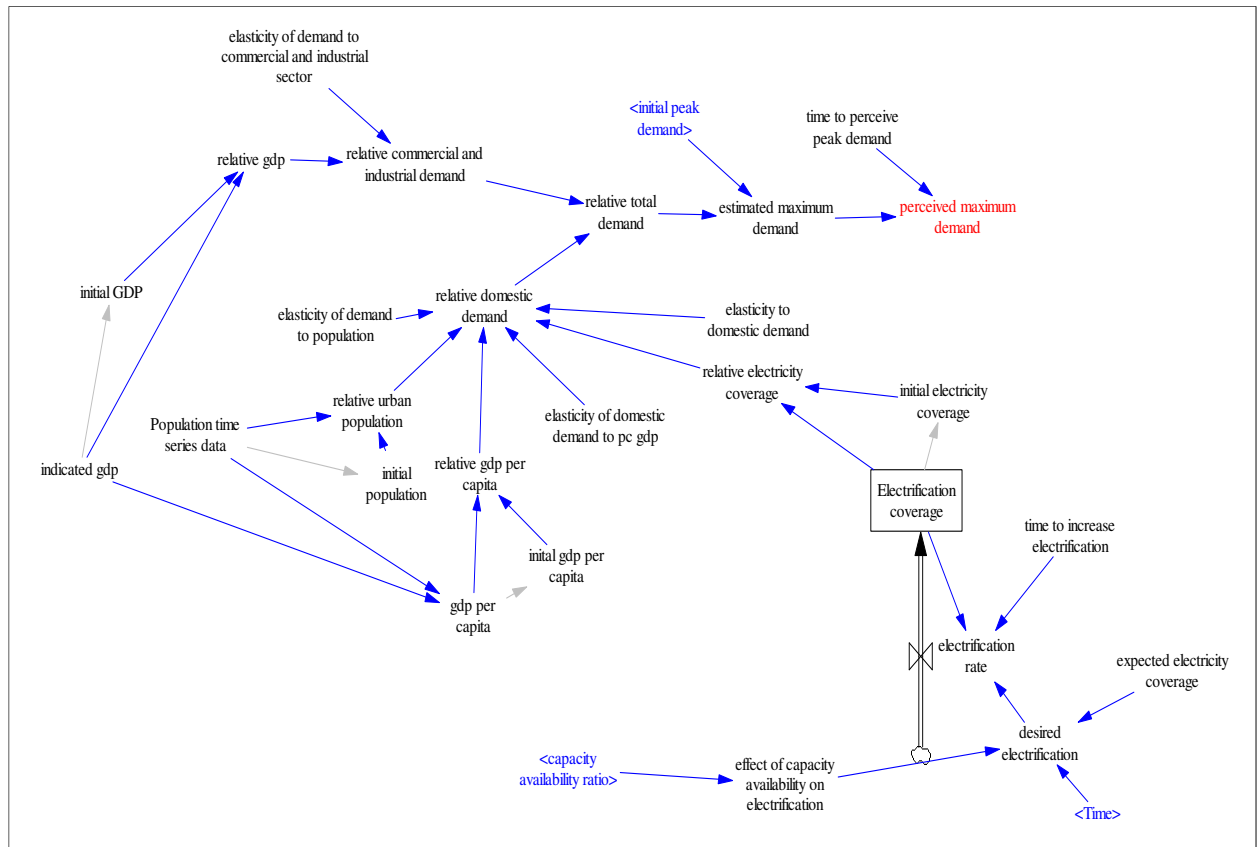


Figure 27: Demand/Supply sector model

Domestic Demand

For the purpose of our model three main variables are used in estimating domestic demand for electricity. First we posit that domestic demand for electricity is influenced by the size of the population, being it urban or rural. All other things remaining constant, housing needs for a population increases when the size of the population increases. This will eventually call for electricity to meet domestic needs. Relative to the rural population, urban population easily gets connected to the power grid because of their easy access to the grid. Extending electricity to rural areas requires investments in transmission and distribution infrastructure, a task that involve long/medium-term plans. Second, we posit that increasing electricity

coverage to the rest of the population by way of expanding the power grid will create demand for electricity as households will tend to switch from their traditional fuels to this modern form of energy for their domestic activities such as lighting, cooking, refrigeration, and so on, *ceteris paribus*. And third, we conceptualise that the domestic demand for electricity responds to the income levels of households. In our model, *Per capita gdp* is the indicator of the population's income level. Households demand for electricity rises as income levels rise. *Relative domestic demand* (figure 27) seeks to measure changes in household demand in relation with changes in per capita gdp, population and electricity coverage. The national drive to ensure universal access to electrification, in line with the MDG's target 1, is ongoing. In line with these efforts, we posit that achievement of this goal is affected by electricity capacity availability; such that if there is more capacity available then network expansion effort is boosted, and policy makers will be more willing to extend power supply to especially the rural areas.

Industrial and Commercial Demand

The main indicator for industrial and commercial demand for electricity as computed in our model is Gross Domestic Product (GDP). We hypothesise that an increase in production activities will trigger more commercial and industrial use of electricity *ceteris paribus*. This is represented in our model as *relative commercial and industrial demand* (figure....) which is the measure of changes in 'non-domestic' electricity demand with demand in year 1990 as base.

Estimated maximum demand

In computing *estimated maximum demand* (figure 27) we use optimization (a statistical tool in our program) to estimate the responsiveness of demand to changes in: electricity coverage, per capita GDP, population, and commercial and industrial demand. Our estimate of demand is compared to historical peak demand time series. Having estimated maximum demand, we then proceed to compute *perceived maximum demand*, a parameter which accounts for the time lag between collecting and processing information about maximum demand. It is formulated as a first-order information delay function with a delay time of one-quarter of a year. To the extent that obtaining information about demand and using it in planning plant capacity do not happen at the same time, we assume a minimum of three months for this time

delay. *Perceived maximum demand* feeds back into the hydro and Rops sector. It is used in adjusting the ultimate goal for plant capacities in those sectors.

Reliability and Consumption effect

In the power industry unexpected increase in demand, equipment failure, adverse weather conditions can cause serious challenges to the Utility’s service quality. Many customers can be subjected to long periods of blackout if the Utility does not have enough reserve capacity as a buffer. When the situation is grave the Utility could resort to power rationing. Capacity availability ratio in our model gives an indication of how much capacity there is above or below the target Capacity margin. We assume that if capacity availability ratio decreases *supply reliability decreases* (figure 28) as well. Supply reliability is considered as a state that changes with changes in its flows. Supply reliability by our definition is the measure of the Utility’s responsiveness to restore power interruptions caused as result of some of the conditions aforementioned. Supply reliability ranges from 0 to 1. With higher capacity availability ratio we assume that the Utility will be able to restore power quickly when the worst happens to their equipment. Indicated capacity, which is the effected change in supply reliability, is anchored on the initial supply reliability; it changes with as capacity availability ratio changes through an effect variable—*effect of capacity availability ratio on supply reliability*. *Supply reliability* then adjust to *indicated reliability* with time.

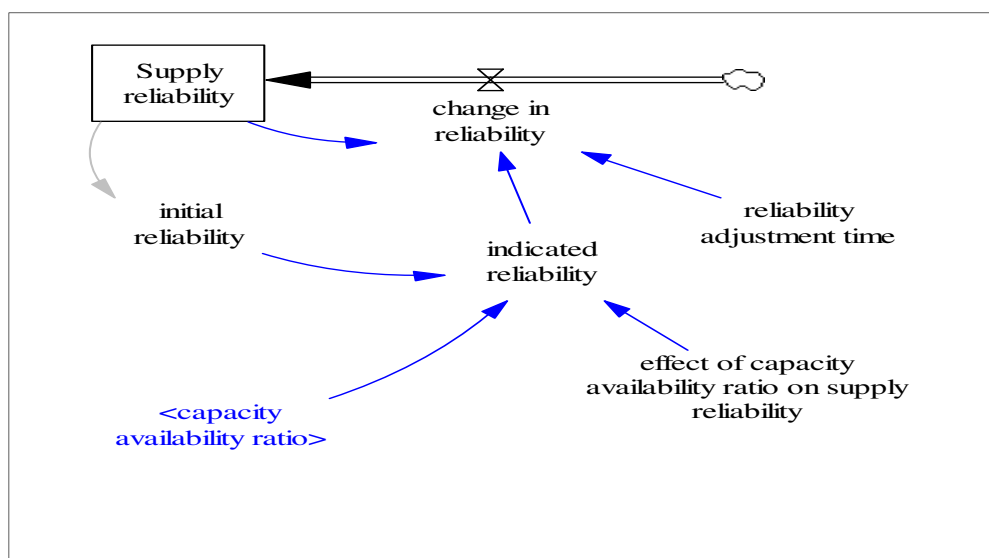


Figure 28: Supply reliability

Supply reliability eventually will impact consumption. Low supply reliability will lead to lower electricity consumption, then this assertion sets in: more consumption will generate higher production (GDP). Figure 29 shows the effect of electricity consumption on indicated GDP. All other things remaining constant, as the Utility improves its supply reliability electricity consumption is expected to rise, leading to growth GDP.

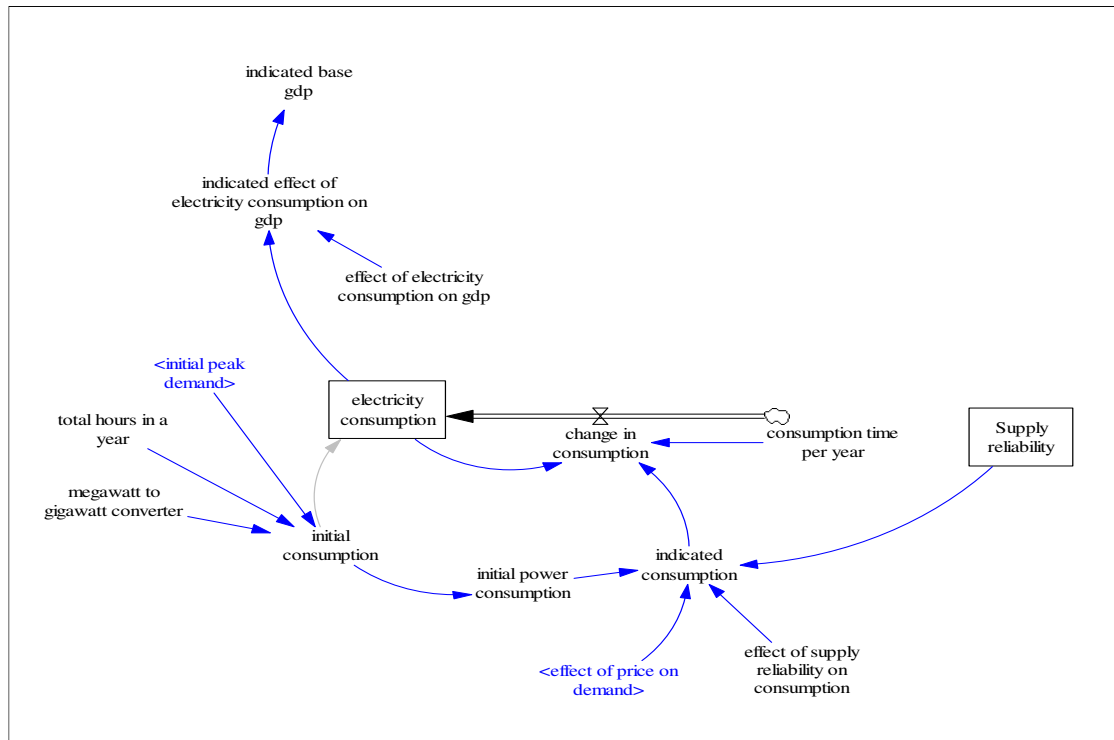


Figure 29: consumption model

Cost and Price sector

This sector figure 30 shows how changes in the cost structure of the Utility affect pricing of electricity. A boost in power plant capacity will increase not only fixed operating cost but also variable operating costs. In order for the Utility to cover its costs it would increase its price per unit generated. The unused electricity, associated with the capacity (reserve) margin, also forms part of the Utility's cost structure. This means that higher Capacity margin culminating in high capacity availability ratio raises cost of operation for the Utility. These costs are then passed on to the consumer in the form of price increases. While electricity

prices increases curtail consumption, it serves as motivation for the utility to produce more as more profit is likely to be reaped from the high prices, especially in a competitive market.

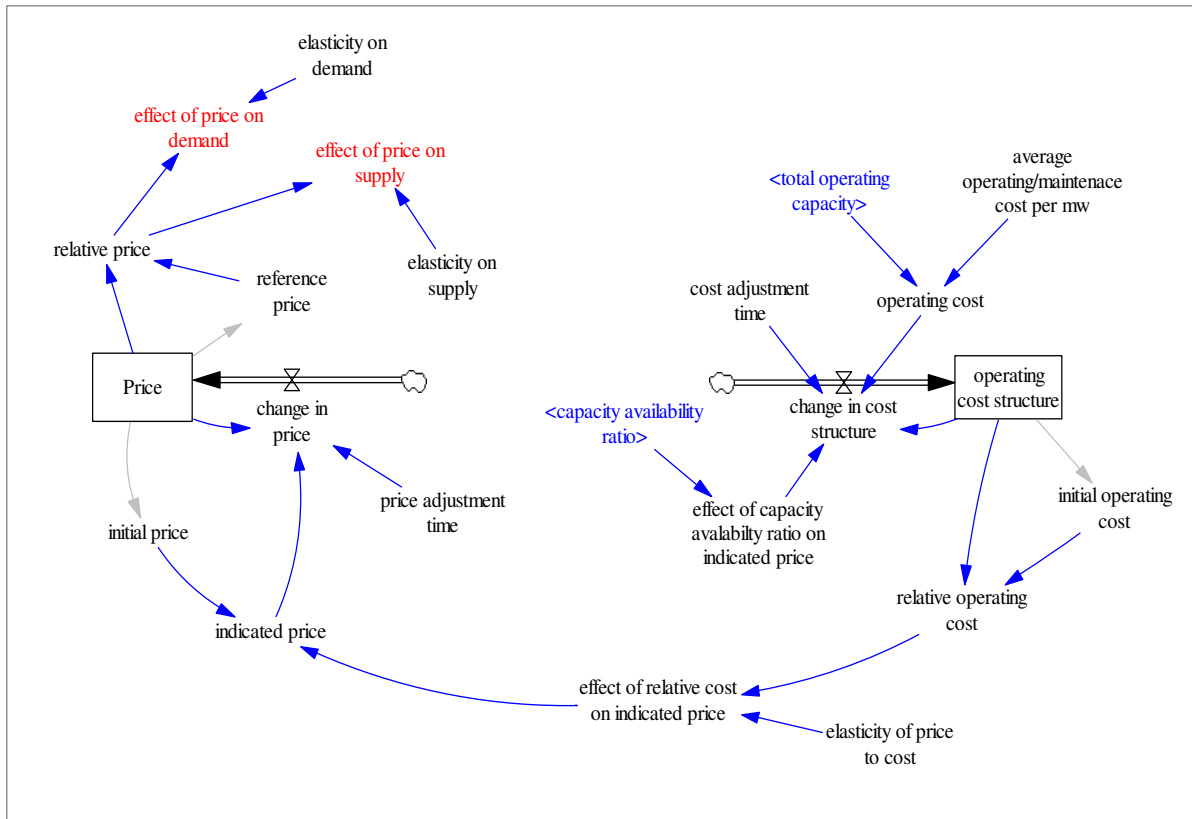


Figure 30: Cost and price sector

Figure 31 shows the entire demand/supply sector model.

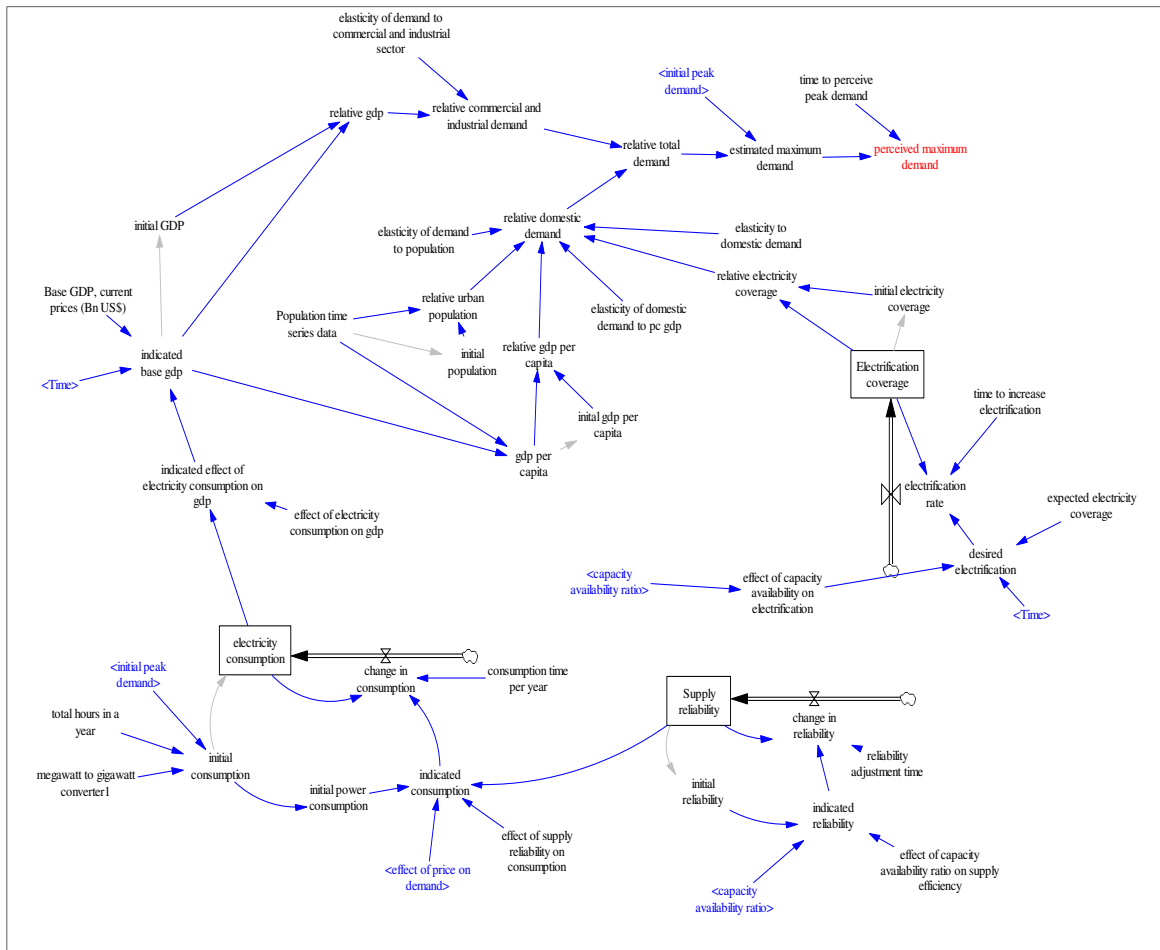


Figure 31: Summary demand/supply sector

5. ANALYSIS

The goal of our model is to get an understanding of the interplay between electricity infrastructure and the Ghanaian economy as well as to understand how population growth could impact on electricity demand. There is a reinforcing feedback between electricity consumption and economic growth GDP in Ghana as indicated by Akinlo (2008), Wolde-Rufael, 2009). With the system dynamic method, we hypothesise that there are other counteracting feedback loops Loop C3 and C4 and reinforcing Loop R3 that could strengthen or weaken the growth of GDP. In this chapter, we seek to test how these loops interact with and impact electricity capacity and GDP. Our model's behaviour is compared with the projected GDP by the International Monetary Fund's (IMF). The IMF projected GDP for Ghana up to year 2014. Our simulation period ends in 2015, however. See Appendix II for excerpt of IMF's assumptions based on which GDP projections are made. We could not ascertain whether their (IMF'S) projections for GDP factored in additional electricity generation capacity, and if they did, we could not, establish the value of the additional capacity. We therefore assume that the projected GDP by IMF did not take into account any additional electricity capacity.

Discrete modelling technique is used in developing our generic electricity model because of the characteristic nature of the power sector. The power sector is considered to be highly capital-intensive, and plants have long life, and constructions thereof have long lead time, with considerable level of uncertainty in the industry. All these partly contribute to the discrete nature of the power system.

Sterman, 2000 recommends a number of tests for System Dynamics models. Our model's test is going to be based on some of his recommended tests including Behaviour reproduction, Parameter assessment test, Extreme Condition tests, and Sensitivity analysis. These tests are going to be conducted in each sector of our model. Some tests are also going to be based on scenarios. These tests are conducted in order for us to gain a considerable level of confidence in our generic aggregate electricity model.

Herewith we present the test results of our model's behaviour that our hypothesised structure depicts. We test each sector separately.

Behaviour reproduction

Figure 32 shows how our estimated demand compares with historical peak demand. Estimated demand represents the peak demand on the electricity system. Even though our simulation is not of the best fit to historical data, at least it traces the trend in growth of peak demand. Our demand is estimated from trends in population growth, per capita GDP and expected electricity coverage. This demand feeds back into all the other sectors of our model. Demand estimates are used in planning capacity investments, capacity increases coupled with reserve margin changes affects the Utility's cost structure which eventually affects electricity prices; change in electricity prices affects electricity consumption levels. This is in line with our hypothesis that: demand for electricity is mainly driven by population and GDP which then impact electricity capacity. Peak (electricity) demand throughout this period has been increasing because both population and GDP have been on the increase as well.

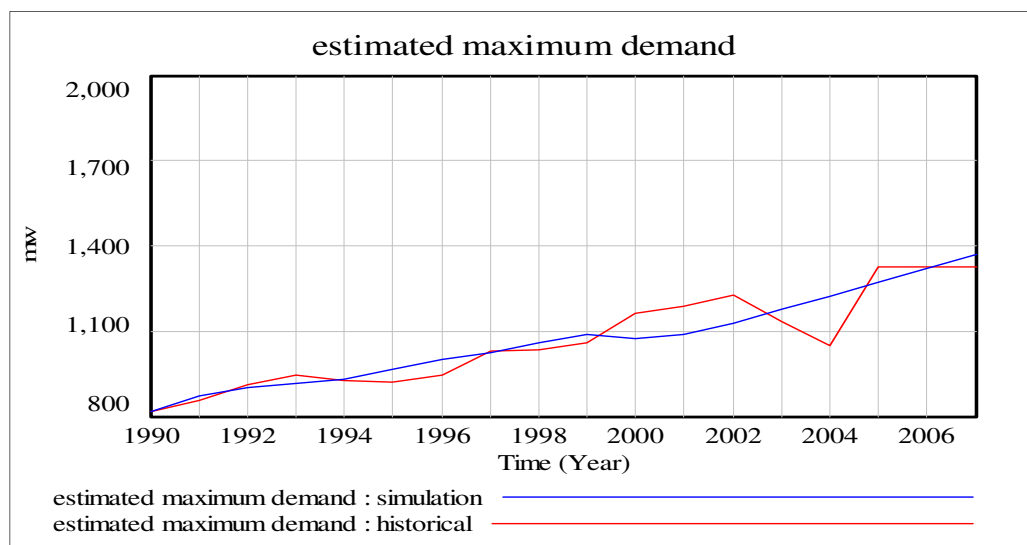


Figure 32: estimated maximum demand

The drop in the historical maximum peak generation until 2004 could be attributed to the period just before the Volta Aluminium Company (VALCO) recommenced operations in 2005. VALCO consumes 35-37 percent of total national electricity consumption (Ghana Energy Commission, 2006). In our model the elasticity of electricity demand to GDP (ie industrial and commercial demand per our model) is 0.1, indicating that GDP is less responsive to industrial and commercial demand; which means that one percent change in industrial and commercial demand lead to 0.1 percent change in GDP. In effect, this means

that the sharp drop in peak demand in 2004 did not have significant impact on GDP, hence our estimated demand trajectory could not account for it.

Compared to the historical data for hydro capacity, our simulation result shows a sharp increase in 2005 figure 33. Between the period 1990 and 2005, hydro power units were taken out for retrofitting work. This explains the downward trend in the historical data between the period 1999 and 2003. After the retrofit work the turbine units became more efficient and with higher output than before. Since our model is an aggregate generic model it could not account for the removal of the turbine units taken out during the retrofit work.

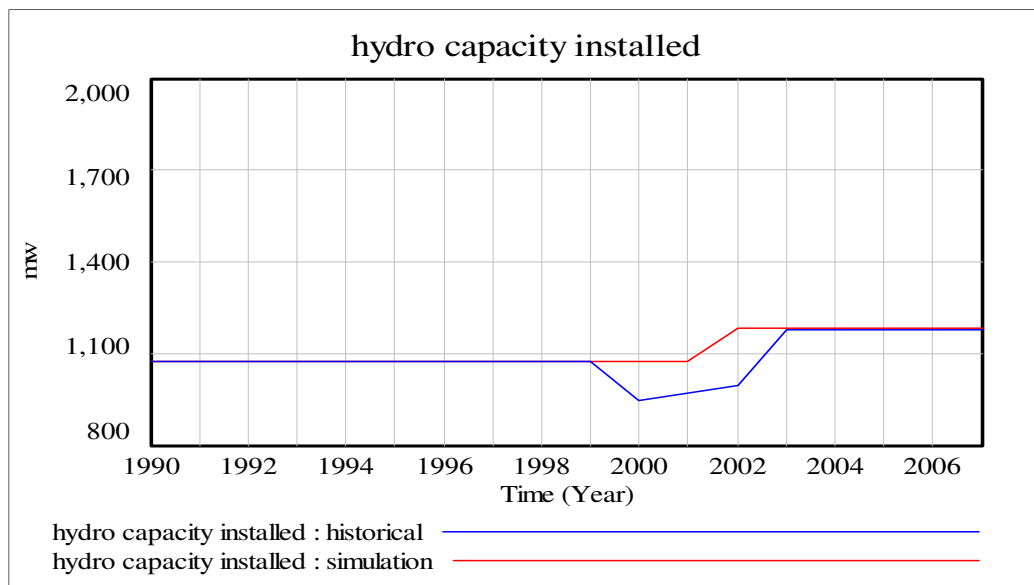


Figure 33: simulated installed hydro capacity

When we extend our time horizon to 2015, our model accounts for the construction of the additional hydro capacity (figure 34). This is in line with the construction of the Bui-dam which began in late 2007. This will exhaust all the hydro capacity by 2011 after completion (figure 35). We choose 400Mw to be the remaining hydro potential because according to sources at the Energy Commission, even though there are potentials for mini-dams of 20Mw/50Mw in the country, their constructions are not economically prudent. The 400Mw we choose refers to the hydro potential currently being tapped on the Black Volta River at Bui.

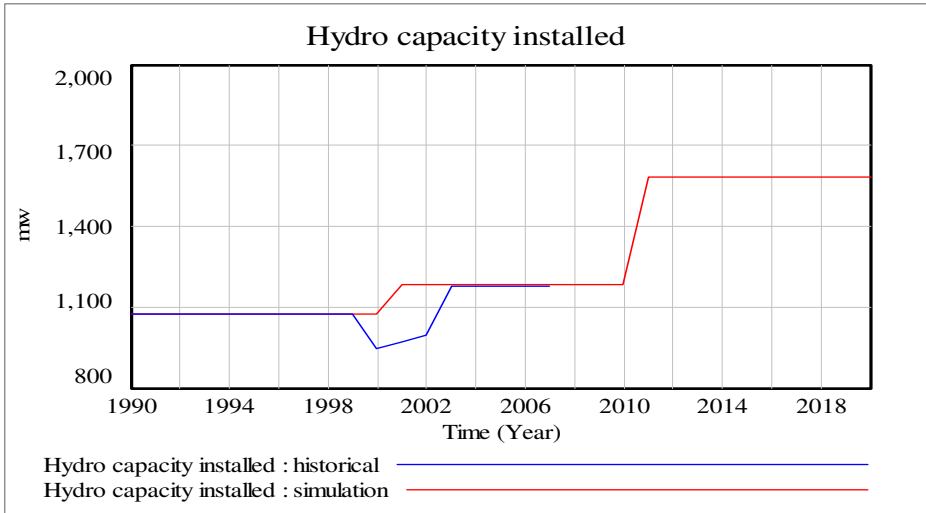


Figure 34: Hydro potential capacity construction

Figure 35 shows the pulse investment in hydro investment. Investment (in hydro construction) starts in year 2007 as the simulation curve indicates figure 34, reaching the peak of 400Mw; and in year 2011 construction is complete and the hydro plant now becomes operational by beginning of 2012.

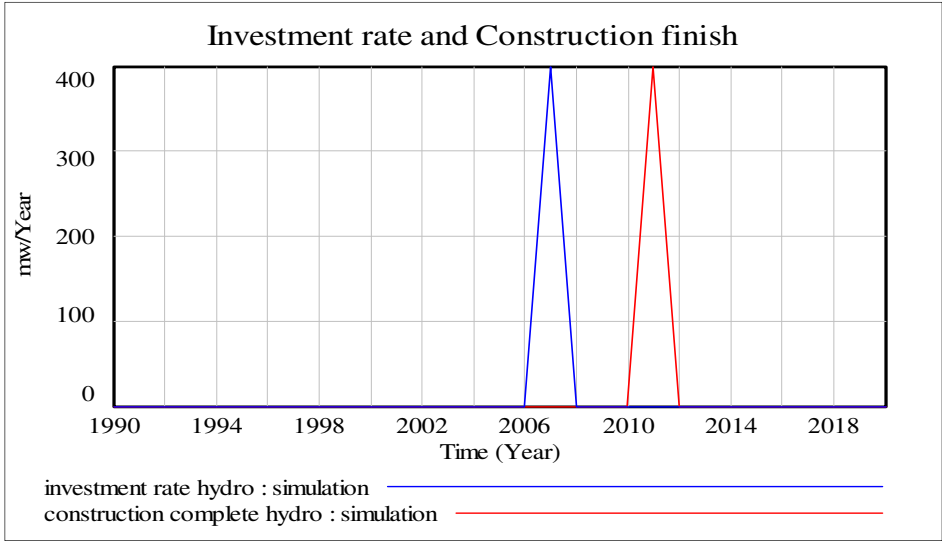


Figure 35: hydro investment rate and construction

Since we seek to draw a link between electricity and economic production, we would like to show how the GDP input in our model is used. Because changes in GDP do not have immediate effect on electricity consumption patterns, we modelled our gdp input from IMF's database as a first-order information delay, with delay time of one-quarter of a year (ie 3 months). We assume that changes in GDP patterns will begin to have effect on electricity consumptions after a period of three months. Figure 36 shows the delayed GDP input, with

indicated base gdp—the input to our model—lagging 3 months behind IMF’s estimated and projected GDP, *base GDP*. Our comparison begins in year 2007.

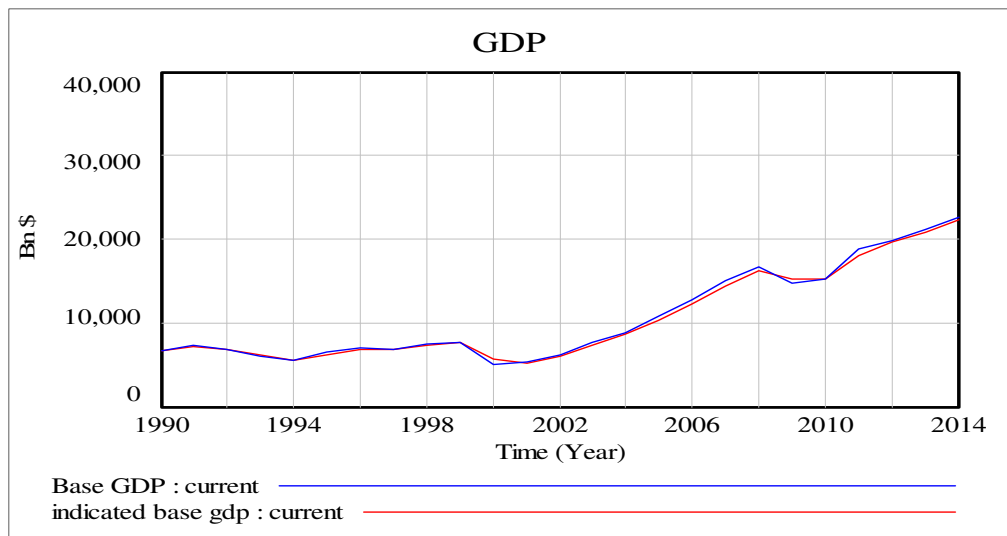


Figure 36: GDP input

Extreme Condition tests

Here we test how robust our model is in extreme conditions. “*Robustness under extreme conditions means the model should behave in a realistic fashion no matter how extreme the inputs or policies*” (Sterman, 2000 p. 869). To conduct this test we cut the supply of electricity to the economy, by cutting Loops C1, C2, C3, C4, R2, and R4. Under this test our model shows that there is no hydro potential; inflows to and out flows from the stock of installed hydro capacity are zero. The behaviour of *indicated base gdp* in figure 37 is not zero because electricity is not the only source of energy for production. Without electricity some production process and activities still go on in any economy. Companies would produce their own electricity from other expensive sources, those who cannot meet the rising costs would wind up; others would resort to imports of cheaper goods in order to remain in business. Our model shows that demand nosedives because there is no electricity supply. Production tends to rise a bit figure 37 after 2010, indicative of the possibility that production activities are gaining some ground, probably because the service industry which is less electricity intensive starts to be more innovative to increase their output. The sharp drop in gdp immediately after the withdrawal of electricity in 2007 could be attributed to the fact that many producers were

caught unawares with the abrupt power outage and production processes grinded to a halt, until new power sources are sought after. Losses would occur and institutions would downsize. Incomes will drop, but production as our model depicts would not be nil, especially with the less-electricity-intensive agriculture sector being the mainstay of the economy (see appendix III for simulation values for indicated base gdp).

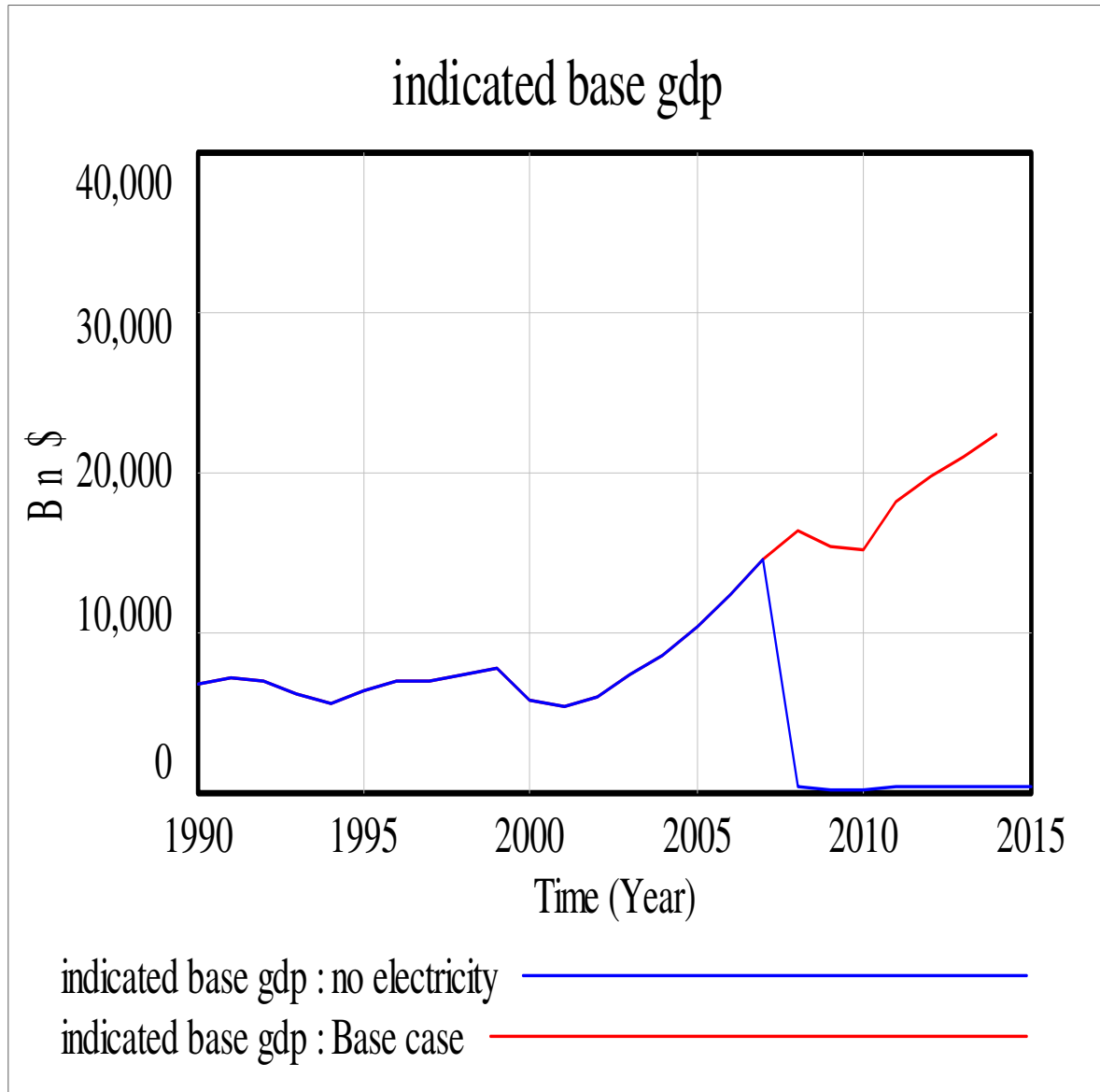


Figure 37: indicated gdp under extreme condition

Parameter assessment test

Under this test we assess how some key parameters in our model compare with real world values.

Hydro Sector

Variable	value
Average installation time hydro	4 years
Capacity adjustment time hydro	2 years
Average lifetime hydro	30 years
Reference capacity margin	0.25

Table 5: parameter assessment-hydro sector

Average installation time hydro is chosen to be 4 years because the 400 Bui Dam currently under construction was initially expected to be completed by December 2011 after construction began some four years ago.

Capacity Adjustment time hydro is chosen to be two years because we assume that a period of two years is enough time to obtain estimates of demand that are representative of consumers' sustained demand. Given that there are a lot of bureaucratic delays in implementing power plant investment decisions, especially with the Utility being publicly owned, we assume that two year interval for taking hydro-stock is essential, so that supply shortfalls are noted in time for appropriate actions to begin early enough.

We conservatively choose 30 years for *Average lifetime hydro* as the Utility (VRA) expresses optimism that the retrofit work on the dam will "ensure the safe and efficient operation of the station for at least another 25 years of operation". *Average lifetime hydro* determines the value of plant capacity that is attributable to depreciation yearly. The VRA states in another document that the life span of hydro generating plants and equipment is up to 45 years.

As discussed in earlier, the US plans and maintains an average capacity margin of 20% figure 9. We choose 0.25 for our model for the following reason: since the Ghanaian electricity market is a developing one there is the tendency for high surges in demand than in the US market which is developed and relatively stable. The 0.25 reference capacity margin may not guarantee reliable and adequate power supply but it is enough to provide reprieve against long periods of power outages. Keeping the reference margin very high could result in high operation cost which will eventually reflect in prices.

Demand/Supply sector

Variable	value
elasticity of demand to commercial and industrial sector	0.1
elasticity of demand to population	0.711349
elasticity to electricity coverage	0.187857
elasticity of domestic demand to pc gdp	0.01

Table 6: parameter assessment-demand/supply sector

We estimate the above elasticities (table 6), given the trends in their input. We believe these elasticities are close to reality. For instance the *elasticity of demand to population* of 0.711349 (relatively higher) gives an indication that growth in population has a greater impact on electricity demand. It is well known that electricity connectivity is quite easier for the growing population in the urban areas than in the rural areas. Settlements in the urban areas are clustered together making it possible for households to connect to the grid with relative ease. To add to the demand, urban population has been on the rise: from about 45 percent (of total population) in year 2000 to a little above 50 percent in year 2008 (World Development Indicators, 2009).

We believe 0.187857 as the responsiveness of electricity demand to electricity network expansion to rural areas, especially, gives a clue about the rural folk's ability to drive electricity demand as much high as their limited income level could permit them. It is also thought that the new arrival of electricity in rural communities paves the way for businesses and job opportunities which would take some time to be established. Hence electricity network expansion may not generate huge demand for electricity, at least not in the short-term.

As explained earlier, *elasticity of domestic demand to pc gdp* represents our income elasticity to electricity demand. Our income-demand relationship (0.01) is not so strong compared to the example given of one metropolitan area in the United States in Wilder, et al (1975) that “*if gross family income grows by 6 percent per year, the residential demand for electricity would grow by about 2 percent per year... ceteris paribus.*” This would produce income

elasticity of about 0.3. From their research Wilder, et al (1975) indicated that residential sizes [in the studied municipality] strongly impact electricity consumption, because there is a relation between residential sizes and income levels. Such kind of study is not known to have been carried out in Ghana yet. There may be many more competing needs and services that households in developing countries are likely to apportion their rising meagre incomes among, which is why we believe low income elasticity to electricity demand should suffice.

We now carry out some tests based on two main scenarios as we try to build confidence in our model.

Scenario 1

In this scenario, we test how only hydro capacity without any additional capacity whatsoever, assuming that there is no hydro potential remaining. Up until 2007 there is 550Mw thermal capacity in the electricity mix. The assumption in this scenario is that there is no thermal capacity in the generation mix after 2007.

Without the construction of additional hydro capacity after 2010, our simulation result shows that the removal of all power sources from the economy will cause GDP to take a sharp downward trend in the year after; and then somewhat oscillates around values comparable to 1990's. This is to be expected because heavy reliance on solely hydropower by the growing economy would deteriorate supply efficiency, frequent power cuts would be experienced, and by way of managing demand the Utility resorts to rationing the inadequate power supply to all the various demand sectors. Consumption crushes leading to low production relative to the base case figure 38.

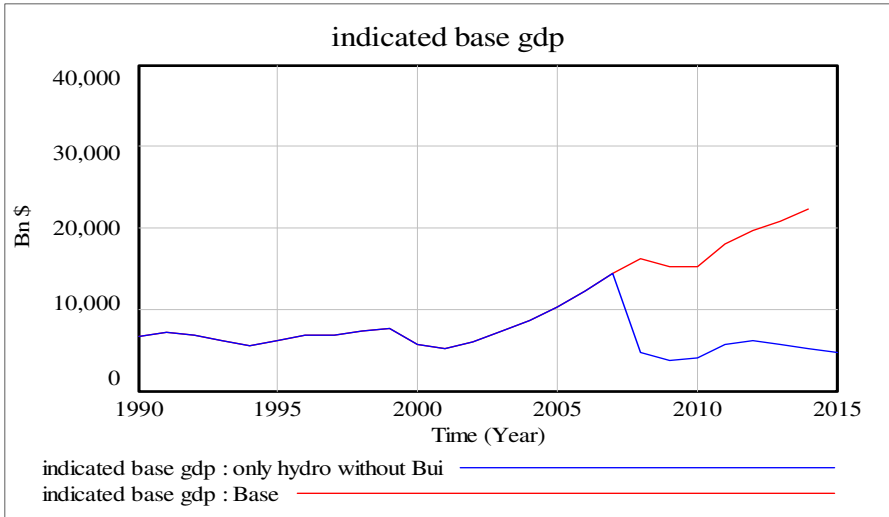


Figure 38: indicated gdp under only current hydro power

Scenario 2

This scenario tests our model’s behaviour when additional hydro capacity is introduced. With the coming into operation of the Bui Dam in 2011 it is expected that, all other things remaining unchanged, production activities are expected to rise, as supply efficiency improves (compared to the scenario 1). This will lead to consumption peaking steadily to with production improving figure 39.

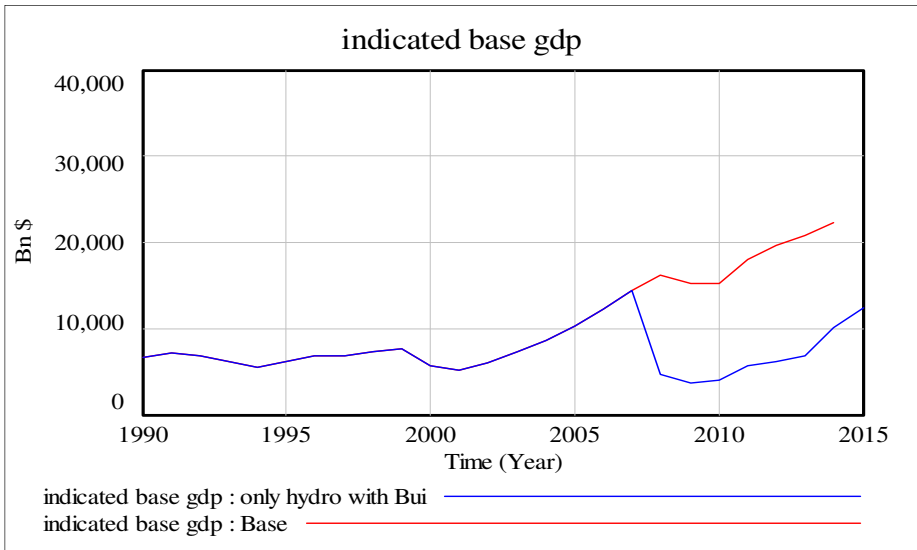


Figure 39: indicated gdp under total hydro power

In both scenario 1 and scenario 2, indicated base gdp falls below IMF's projected gdp, indicating that electricity production from solely hydro sources (ie Akosombo, Kpong and Bui hydro dams only) could not facilitate high economic growth.

6. POLICY TEST

From the foregoing scenario tests, and the other tests preceding it, we have come to the conclusion that the total electrical energy from hydropower is not adequate enough to improve the performance of the economy. We develop the *Rest of Power sector* to supplement the hydro sector by adopting the generic structure for the hydro sector for the *Rest of power sector*. Rops is expected to respond to changes in demand by adjusting power capacity in response to the changes in demand. As described in earlier this sector aggregates capacity from all other potential sources: thermal (gas-fired, coal-fired, oil-fired) plants, with renewables like wind and solar. Our generic model policy structure seeks to explain the structure behind behaviour of the power sector and the economic sector. We test our policy structure as well to see its robustness.

Assumption:

We assume that there is no electricity capacity from other (non-hydro) sources in the economy from 1990 to 2006 when we implement this policy structure. This implies that electricity capacity available in 2006 is 1180Mw.

Based on our estimates of electricity demand and the interaction between the various sectors of our models, production activities drive up economic growth steadily figure 40 with the introduction of additional power capacities: 400mw introduced from the hydro sector figure 34; and in response to the inadequate capacity in the hydro sector 4500mw more capacity is introduced from the Rops sector in 2006 figure 41. It is noted that the introduction of the additional powerplant capacities did not have immediate effect on *indicated base gdp* because of some delays in the system: eg electricity consumption does not have immediate effect on gdp, just as gdp is not immediately computed and known, and it takes time for companies to make capital investment that impact on electricity consumption, and as well households income rise will not change their electricity consumption immediately. Consumption increases gradually to generate the increased production later on, above the base case.

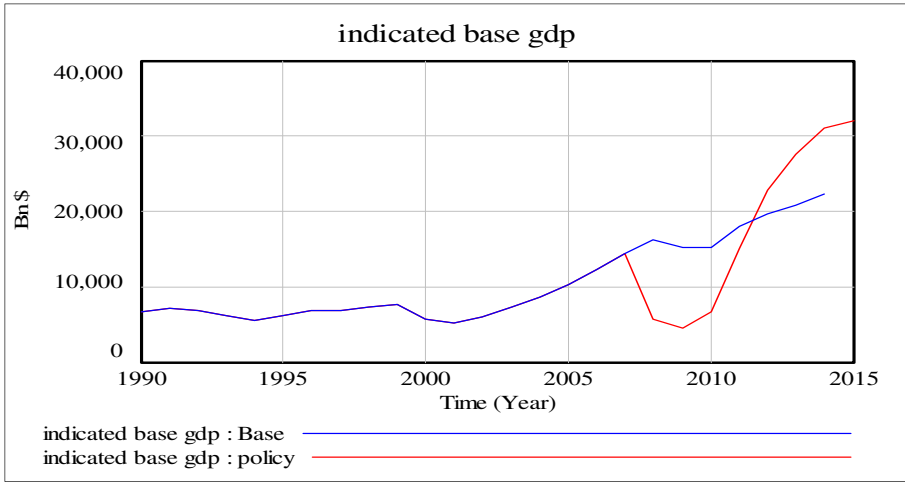


Figure 40: indicated gdp under additional power capacity

The corresponding new capacity from the *rops* sector that generated the increasing indicated gdp in figure 40 is a little above 4500Mw figure 41. The assumption underlying figure figure 41 is that investments in the *Rops* are made every 5years after a careful study of trends in demand drivers.

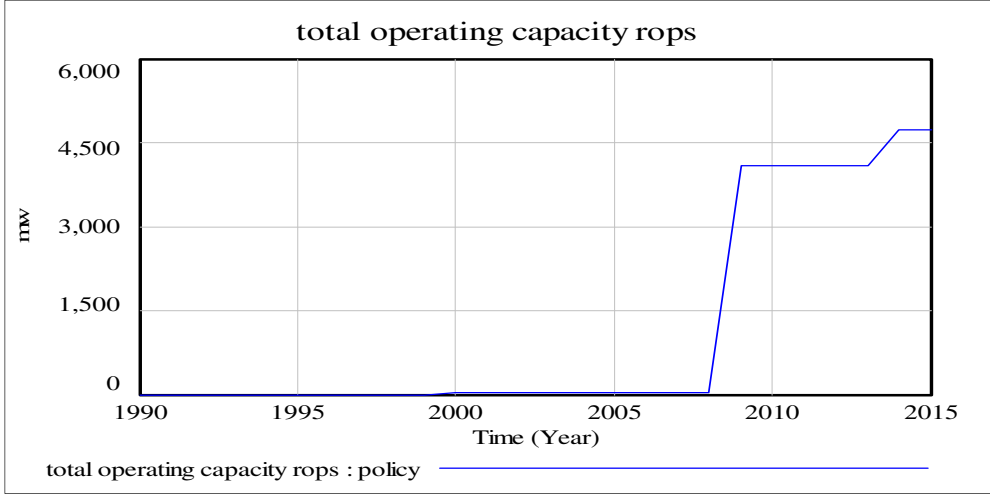


Figure 41: additional capacity from non-hydro

This when added to the existing total hydro capacity will bring total power capacity to a little above 6000MW figure 42.

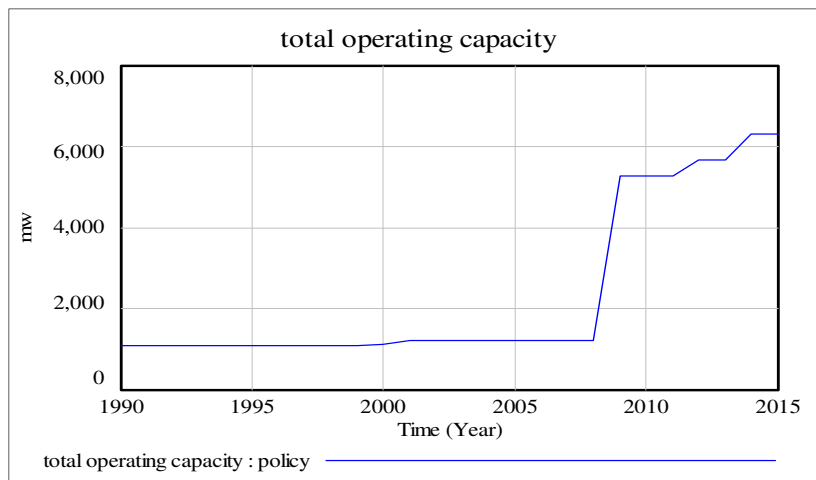


Figure 42: total operating capacity

The simulation result of our model figure 42 seems to relate to the estimation of the power sector ministry. In a policy document²³, the Ministry of Energy (MOE), has set an objective to increase electricity generation capacity to 5000Mw by 2015 from various sources including expanding thermal proportion in the electricity mix. What is unknown, at the time of this paper, is the growth rate that the additional capacity is expected to facilitate. The common denominator to both estimations, however, seems to be that improving the power sector infrastructure would lead to growth.

Our model does not take into account government budget and the cost of installing capacity generated by our model because incorporating these two factors in our model will require additional modelling effort, considering the limited time at our disposal. However, see discussion of these factors in section 7 (*discussion and challenges*).

²³ Energy Sector Strategy and Development Plan by the Ministry of Energy.

Sensitivity test

Sensitivity: capacity adjustment time rops

Our model is sensitive to *capacity adjustment time rops* in our policy structure. *Capacity adjustment time rops* refers to the time the Utility take record of discrepancies between their desired production and actual capacity installed.

Holding *investment time* constant (at every 5 years), the shorter the time to adjust capacity the faster the stock of installed capacity adjusts to *desired capacity rops* figure 43. A shorter time means that the Utility responds quickly to changes in demand patterns and invest in plant capacity as quickly as possible. Three values were chosen for *time to adjust capacity rops*: 1, 2, and 5 years. The stock of capacity in the rops sector is sensitive to its capacity adjustment time. Obtaining demand data yearly is quite an expensive exercise, and even more expensive is the cost for new power capacity. While One (1) year is not a realistic value for our *time to adjust capacity rops* parameter, five (5) years for this parameter deteriorates *supply reliability* figure 44 because of the insufficient capacity it generates compared to the results of the other parameter values.

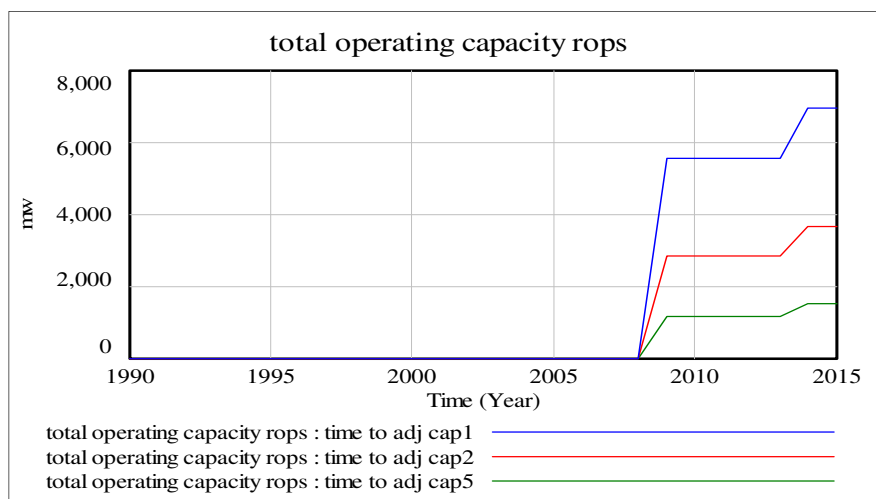


Figure 43: Sensitivity of 'time to adjust capacity rops' on capacity

A shorter time to adjust capacity produces high level of capacity which improves the system reliability figure 43 because the system would have enough capacity margin (buffer) in the immediate short-term, in which case the system becomes relatively reliable. When this

happens, consumption grows steadily. GDP would improve eventually because production equipment are more likely to enjoy uninterrupted power supply.

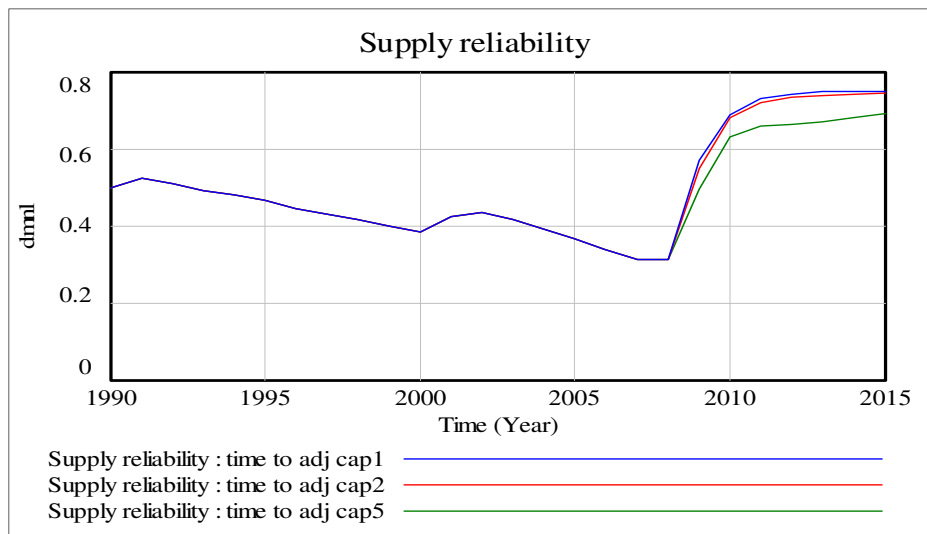


Figure 44: Sensitivity of time to adjust capacity on supply reliability

Sensitivity: investment start rops

Our model is also sensitive to *investment start rops*. This variable represents the cyclical time for making investment in the rops sector; it introduces discrete investment time with equal intervals. As mentioned earlier, the Rops sector comes into effect in 2006 to supplement the hydro sector. Investing in the Rops with shorter time intervals in response to changes in demand will produce high stock value for plant capacity in a shorter time than making investment with longer time intervals. Time period of 2 years for *investment start rops* results in the highest capacity value, followed by that of 5 years figure 45. Capacity values for times 10 and 15 years are the same in the short term until 2015. This is so because as population and other factors drive demand are ignored until the set time to initiate investment is due (ie 10 or 15 years). If the Utility responds quickly to short-term fluctuations in demand, it is more likely to aggressively increase its capacity far in excess of demand. If the utility takes longer time to assess changes in demand, it is more likely to adjust its capacity based on sustained changes in demand. The risk here is that if it takes the Utility too long time to invest in capacity, demand could outstrip supply, leading to reliability problems in the utility's system leading to decline in consumption. Capacity investment could be made based on deflated demand level.

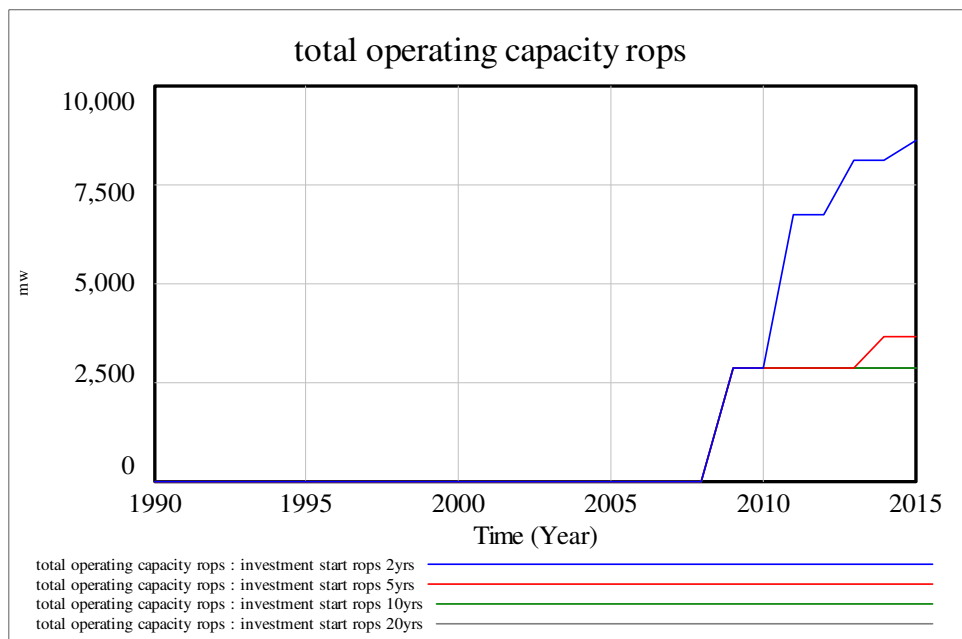


Figure 45: sensitivity of 'investment start rops' on total capacity

These levels of capacity have cost implications and the Utility will be reluctant to make new capacity investments in short interval, especially when they are not in good financial standing. However, if government intervenes, it does so at the expense of other sectors of the economy. Yet, adequate capacity could be a source of foreign exchange as sales through the proposed West African Power Pool to neighbouring countries could generate more revenue.

Sensitivity: Cost structure and price effect

It has been observed from our simulation that our model's behaviour is sensitive to *elasticity of consumption to price*. We choose three different values (-0.05, -0.1, -0.5) to run this test. Our estimate excludes -1.0 (for our price elasticity of consumption (demand)) because electricity is conceived of not as a luxurious good. The result shows that the margin with which electricity consumption decreases is greater when *elasticity of consumption to price* is -0.5 than it is for the other values figure 46. There is no established data about the extent to which energy consumption levels shrink with price increases, but it is generally known that electricity consumption is not very responsive to price changes. In an era of rising cost of

electricity, households still need electricity for basic activities such as lighting, cooking, cooling and refrigeration. The major effect of energy price hikes likely reflects in the prices of goods and services, because of the indispensability of electrical energy in production processes. If price elasticity of electricity demand (consumption) is unitary then, as remarked by Wilder and Willenborg in their paper, *Residential demand for electricity: a consumer panel approach*, it would “...suggest that the price mechanism could be an effective way of rationing electricity during potential future shortages” (Wilder and Willenborg 1975).

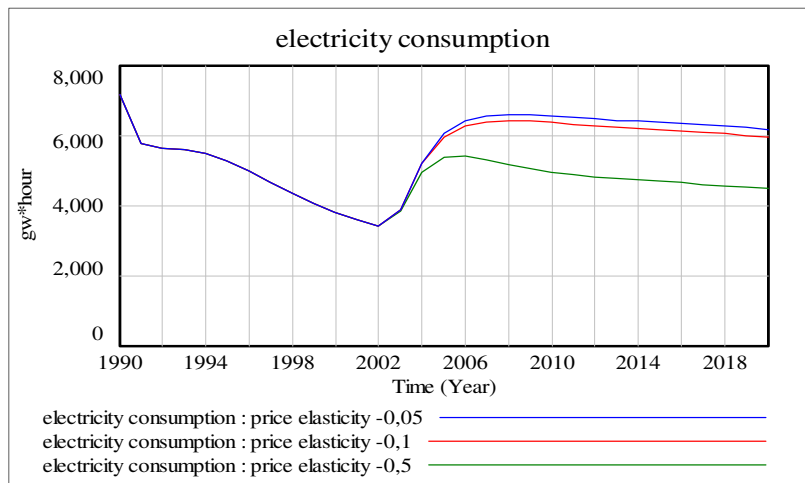


Figure 46: sensitivity of price on consumption

As Consumption in figure 46 took a downward trend because of high prices, pressure on the power system reduces and the power system becomes more reliable: this is indicated in figure 47 where the supply reliability curve produced by *price elasticity* of -0.5 lies above that of the other elasticity values.

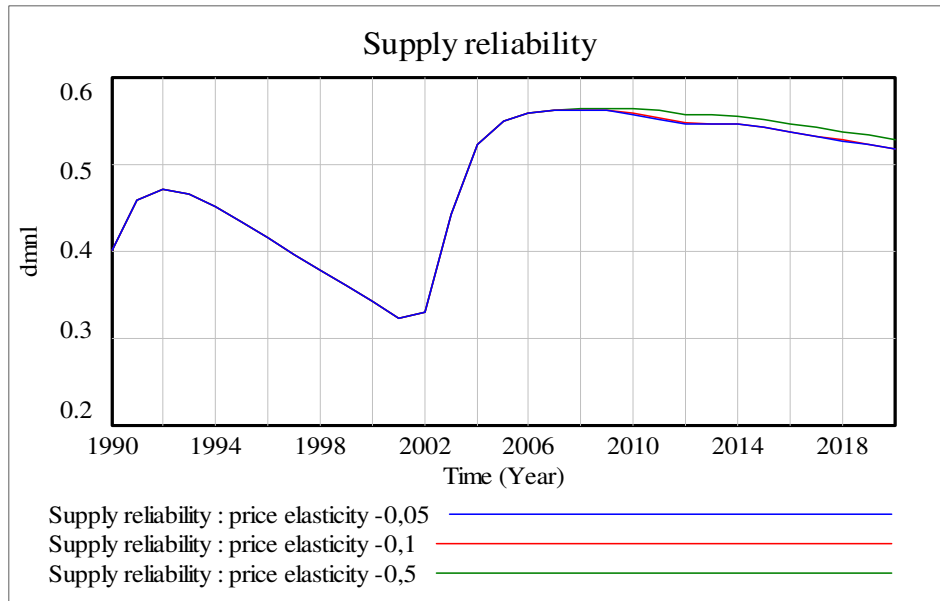


Figure 47 : effect of price on supply reliability

Sensitivity: Price Adjustment

We now assess the effect of the time it takes the utility to slap price increases on consumers. As indicated in the early chapters, price adjustment fall within the ambit of a regulatory commission after negotiations with the Utility. In our model the parameter *price adjustment time* refers to the total time it takes for the Utility’s proposed price to be approved. The utility justifies why its prices should be reviewed, in most cases upwards. An increase in the Utility’s input prices (such as oil or gas prices, if it’s a thermal plant) will contribute to rise in variable cost of production. Another factor that could result in the cost structure of the utility changing is when its fixed cost rises. Fixed cost could rise when plant capacity rises. Additionally, upward adjustment to plant capacity margin also calls for price adjustments in order for the utility to cover the cost of running and maintaining its idle capacity.

The time lag between the realisation of rising operating cost and the approval of rates could have significant effect on consumption patterns especially among consumers who are sensitive to electricity prices. To do this test we choose price elasticity of -0.3, and *price adjustment time* of 0.5,1 and 3. These numbers are in years, and may not represent the actual time for price approval activities.

The longer it takes to approve rates the later the full effect of the price is felt on consumers. Price adjusts quickly figure 48 to its new goal when proposal and approval time is short than it does when the time is long.

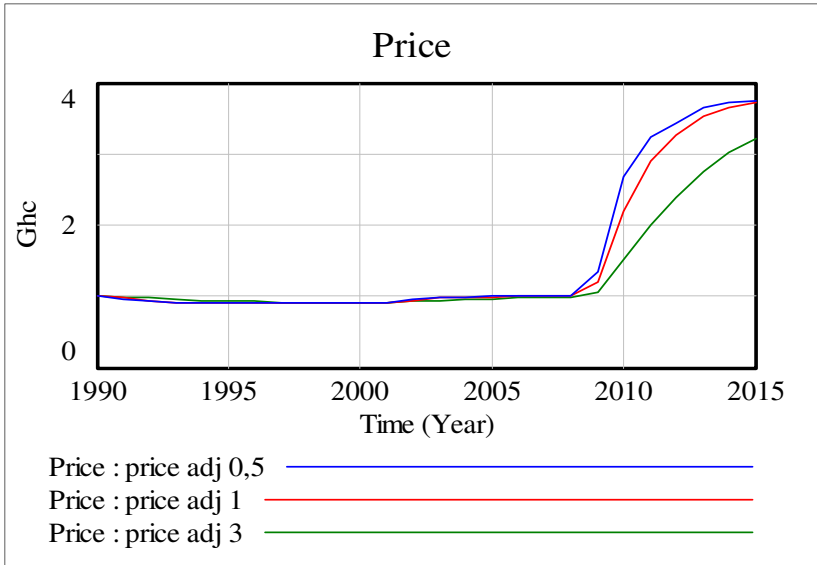


Figure 48: effect of price adjustment time on price

It must be noted that delays in effecting new prices does not mean that there is a reduction in prices; it is only a deferment of effect. The trajectory in figure 48 for times 1 and 3 mean that the final price (which is the peak of the price curve) is reached eventually, but after the lapse of the adjustment time. The effect of price changes on electricity consumption reflects the responsiveness of the consumer to price. After our policy introduction period 2006, consumption increases with the increase in plant capacity. Price adjustment time of 3 yielded high consumption curve figure 49 because of the delay in electricity rates approval: the delay in approval activities keeps consumption afloat because consumers are still paying old rates. The lowest curve is that for which price adjustment takes a quicker effect.

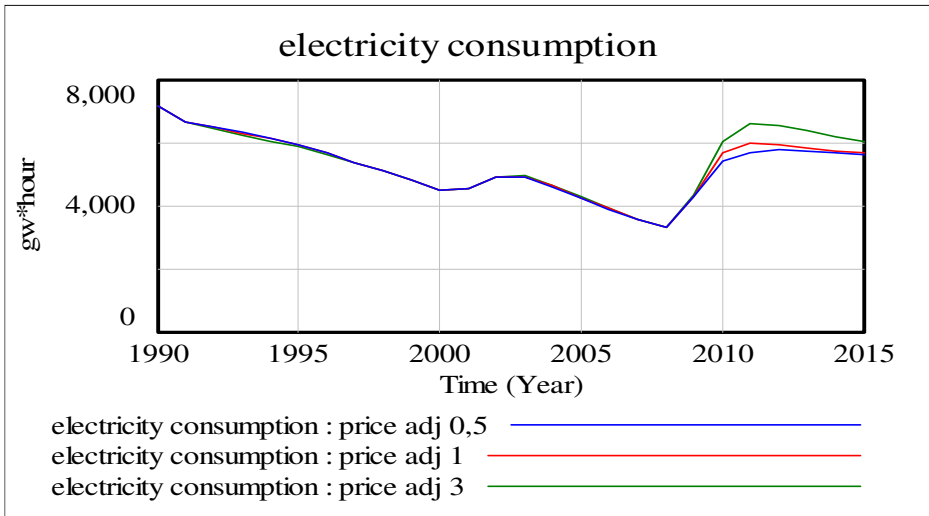


Figure 49: effect of price adjustment time on consumption

Because there is a positive relationship between consumption and gdp, higher consumption as a result of long rate approval time yields high gdp figure 50 in the interim.

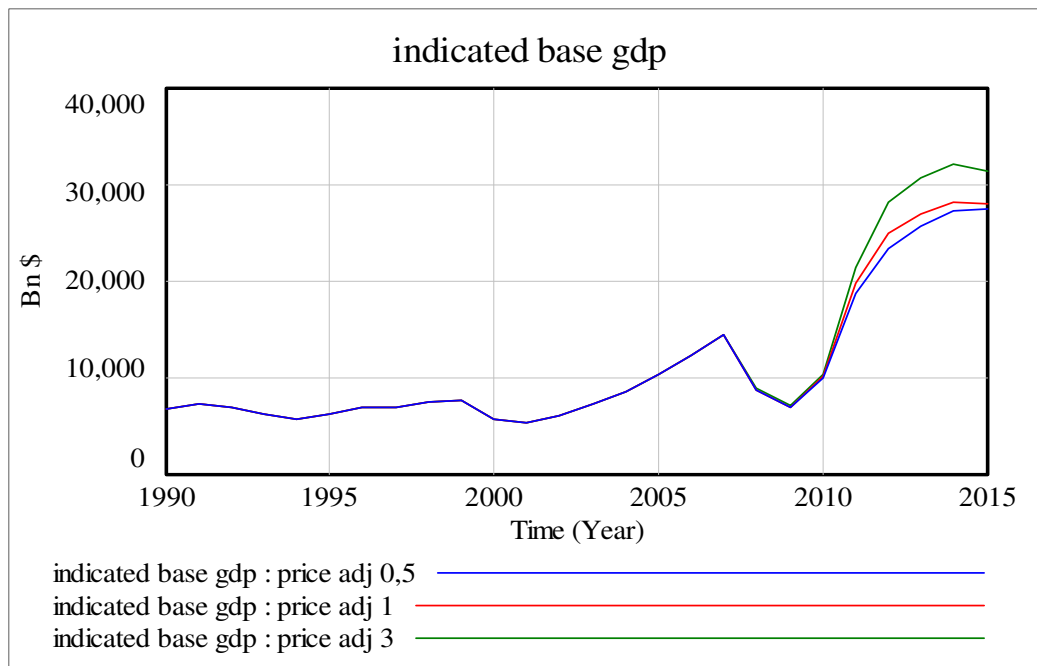


Figure 50: effect of price adjustment time on indicated gdp

Nonlinear functions

Effect of electricity consumption on gdp

The relationship between electricity consumption and gdp is nonlinear figure 51. In constructing this it is assumed that even in the absence of electricity some economic production activities still go on. Again it is assumed that increases in consumption drive gdp slowly and sharply later on; and holding all other things constant, further increases in consumption will not yield as much gdp when the law of marginal returns sets in and gdp will increase but at a decreasing rate as in the developed world.

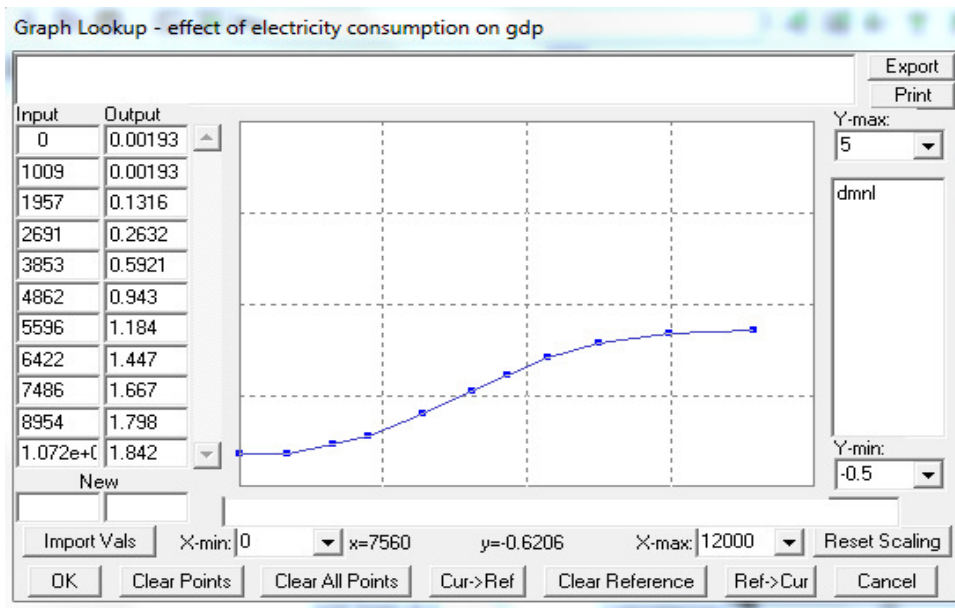


Figure 51: graph- effect of electricity consumption on gdp

Effect of supply reliability on consumption

No matter how worst the quality of service delivery of the Utility may be, consumption of electricity still go on as long as it is available. When the utility begins to improve its supply reliability, consumption will increase sharply. When the utility is at its best with providing reliable electricity, then consumption somewhat stabilizes as more consumers build trust in the service and operate their appliances for long hours without any fear of damages caused by power interruptions. This is the assumption based on which the “*effect of supply reliability on consumption*” graph figure 52 is constructed.

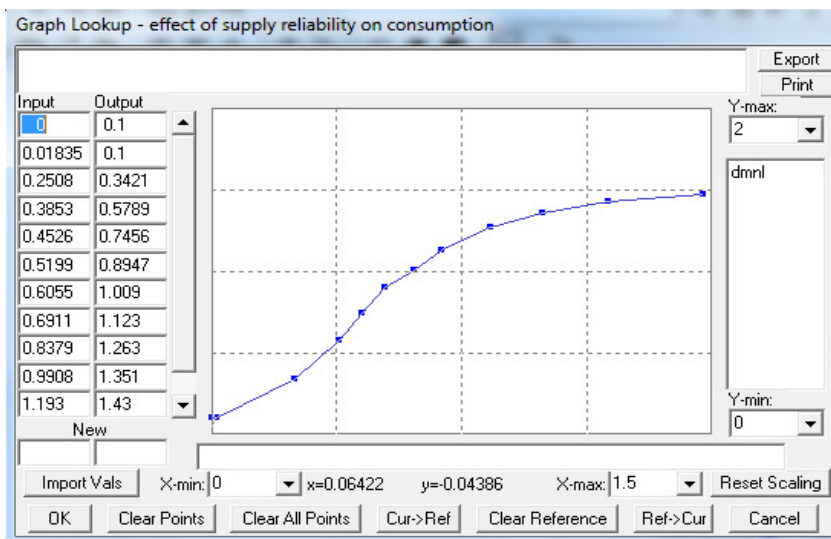


Figure 52: graph-effect of supply reliability on consumption

7. DISCUSSION AND CHALLENGES

Many research findings have emphasised the role of infrastructural development on human well-being. In recent years, however, infrastructural development has received greater attention by many developing nations. Some improvements have been seen from the construction of roads to the building of schools, hospitals to mention but a few, among countries on the growth ladder. Sufficient infrastructure is said to be an ingredient of growth.

In a world bank Policy Research paper on “*The Effects of Infrastructure Development on Growth and Income Distribution*,” Calderon et al (2004) after carrying out studies on over 100 countries have established two main conclusions that:

- Growth is positively affected by the stock of infrastructure assets, and
- Income inequality declines with higher infrastructure quantity and quality²⁴

The report highlights the effect of increased availability, and quality of infrastructure. These conclusions suggest that combating poverty cannot be de-linked from infrastructural development. Energy infrastructure is one of the most important catalysts for growth, as energy forms part of every human and economic activity. Energy and economic growth are directly related Lee (2005), Stern (2000), Wolde-Rufael (2008, 2009), Akinlo (2008), Ebohon (1996).

Electricity, considered as a modern form of energy, equally plays a catalytic role in the development of any economy. Industrial breakthrough (in Norway) came after the widespread introduction of electricity in (Venneslan 2009).

Not only should electricity be sufficient, it should also be reliable to facilitate the growth needed. To ensure its adequacy, electricity infrastructure needs to be boosted through continuous and unrelenting investment. “*Any prolonged downturn in [energy] investment threatens to constrain capacity growth in the medium term...eventually risking shortfall in supply*” (WEO 2009).

Ghana is confronted with inadequate electricity supply. As we learnt from our simulation model and the tests that ensued, maintaining the status quo in the power sector may not bring about high economic growth. Additional electricity capacity is needed to augment

²⁴ See <http://go.worldbank.org/MWLEIS62E0>

production. From figure 41 more than 4500Mw is required from the non-hydro sector to boost electricity generation capacity. From the historical records, there is an existing non-hydro capacity of 550Mw in Ghana. Let us deduct that capacity from our simulated value of say 4500Mw; it will be left with nearly 4000. For the purpose of this analysis, let us assume that the additional non-hydro capacity needed is 4000Mw. What are the cost implications? Assuming that the cost of installing one kilowatt of natural-gas Combined Cycle Power Plant is \$1,200.00/kw²⁵. Our mention of natural gas combined cycle power plant for this analysis is influenced by the fact that these plants are said to have:

*“... a relatively low construction cost and modest environmental impacts; can be used to meet baseload, intermediate, and peaking demand; can be built quickly; and are very efficient.”*²⁶

Our reference is also influenced by the availability of gas in the West African sub-region, through the West African Gas Pipeline project; and the oil-fields off the shores of the country as readily available sources of fuel. Solar, waste-to-energy, wind are other sources, though.

Building the 4000mw capacity may cost not less than \$4,800,000,000.00 (ie 4000Mw *1000kw/mw* \$1200) US dollars. This colossal amount compared to Ghana’s year 2006 Gdp of \$12.729billion²⁷, amounts to about 38 percent. It is quite clear that government single-handedly may not be able to finance these capital-intensive projects. Borrowings and deregulating the power sector are options to be considered. Generally electricity production and productivity have increased after deregulation as a result of the introduction of competition (Arango, Dynner et al. 2006). Government action is urgently needed to speed up growth. Meanwhile, budget constraint is the main limiting factor on government’s effort to provide adequate electricity capacity. But it is within government’s effort to promulgate laws that would allow private enterprises to invest in this all-important sector, while it still holds regulatory and oversight responsibility over the industry players.

²⁵ Figure is based on overnight cost estimate indicated in Congressional Research Service (CRS) Report of 2008. The report defined overnight cost as “... the cost that would be incurred if a power plant could be built instantly. The overnight cost therefore excludes escalation in equipment, labor, and commodity prices that could occur during the time a plant is under construction. It also excludes the financing charges, often referred to as interest during construction (IDC), incurred while the plant is being built”. See: www.fas.org/sgp/crs/misc/RL34746.pdf

²⁶ Congressional Research Service report. For full report see: www.fas.org/sgp/crs/misc/RL34746.pdf

²⁷ Source: IMF’s World Economic Outlook database, October 2009

If the United Nation's Millennium Development goal #1 is to be achieved in 2015, then the current electricity capacity needs to be upgraded. Universal electrification could be achieved by 2015, but what will the implications be if electricity capacity is not boosted? Reliability problems could emerge, as the presence of electricity in communities could lead to higher consumption, *ceteris paribus*.

The main limiting factor in our model is the lack of micro-level data for the various demand sectors of the economy. One of the data sources used in estimating demand is actual peak demand values obtained from the Utility. For the same period we have had conflicting values for peak demand from other sources in the power industry.

Future studies into the key drivers of residential electricity demand would be very crucial in establishing a more accurate estimate of demand growth rates. This would be helpful in planning both capacity and capacity (reserve) margins to ensure sufficient and reliable power supply to facilitate economic growth.

8. CONCLUSION AND RECOMMENDATION

From our model we have gained a considerable insight into the interplay between the power sector and the economy. We employ discrete modelling technique, delays, and nonlinearities in developing our model. Our model provides insight into factors that could influence decisions on power capacity investment, and how power capacity additions could create growth or otherwise.

We present two scenarios, and suffice to say power generation solely from the hydro sector could not guarantee high economic growth. It is therefore important that other forms of energy are sourced to supplement the hydro sector because adequate and reliable power supply will generate the growth needed to achieve United Nation's Millennium Development Goals. While it is not feasible to undertake capacity additions with short intervals because of financial constraints, long delays in adjusting power plant capacity could stagnate economic growth as a result of potential shortfall in supply. Prolonged delay in power investment could, however, risk capacity adequacy and reliability, and eventually result in supply shortfall. Said differently, prolonged delay in capacity investment could weaken demand and constrain economic growth. While frequent investment in power plants in response to surges in demand could be an unbearable cost for the Utilities. Yet, adequate electricity capacity helps improve economic growth.

The relationship between electricity consumption and price is not very strong, to the extent that high tariffs could not be a tool for demand-side management in the event supply shortages. Our test also points to the conclusion that bureaucratic procedures of the utility regulatory commission could be a tool for postponing the effect of price increases on the consumers, however strong or weak price elasticity of demand is.

We recommend the following:

Deregulation

Government holds the key to changing the investment mix in the power sector through its policy regulatory framework. Deregulation of the electricity sector could be a way of sourcing private capital to boost plant capacity. The Renewable Energy Bill which is yet to be passed into law should allow a much more active participation of the private sector (households and businesses, both nationally and internationally) in the power sector.

Time-of-use tariff

As a way of managing demand and to prevent it from surging further during peak hours, the utility could adopt charging relatively low rates for electricity use during off-peak hours in order to spread out the demand on the system.

Capacity margin

To ensure power resource adequacy and reliability, an Electricity Reliability Committee should be established and be responsible for planning and monitoring Capacity margins, as well as setting up of reliability standards and ensuring compliance thereof for the power industry. We recommend 25% as target (reference) capacity margin, below which stakeholders in the power sector should start making efforts for new capacity.

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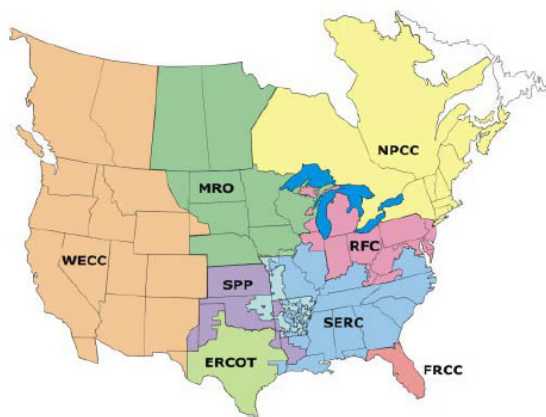
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Appendix I: North American Electric Reliability Corporation

“The North American Electric Reliability Corporation’s (NERC) mission is to ensure the bulk power system in North America is reliable. To achieve this objective, NERC develops and enforces reliability standards; monitors the bulk power system; assesses and reports on future adequacy; and offers education and certification programs to industry personnel. NERC is a non-profit, self regulatory organization that relies on the diverse and collective expertise of industry participants that form its various committees and sub-committees. It is subject to oversight by governmental authorities in Canada and the United States”.
 URL: <http://www.nerc.com/page.php?cid=6>

The NERC Regional Entities in the United States



ERCOT Electric Reliability Council of Texas	RFC ReliabilityFirst Corporation
FRCC Florida Reliability Coordinating Council	SERC SERC Reliability Corporation
MRO Midwest Reliability Organization	SPP Southwest Power Pool, Incorporated
NPCC Northeast Power Coordinating Council, Inc.	WECC Western Electricity Coordinating Council

See <http://www.nerc.com/page.php?cid=6>

**Net Internal Demand, Actual or Planned Capacity Resources, and Capacity Margins by
North American Electric Reliability Corporation Region, Summer, 2009 through 2014**

North American Electric Reliability Corporation Regional Entity	Net Internal Demand ¹	Capacity Resources ²	Capacity Margin (percent) ³	Net Internal Demand ¹	Capacity Resources ²	Capacity Margin (percent) ³
TRE (formerly ERCOT).....	63,518	76,280	16.7	62,412	75,181	17.0
FRCC.....	46,263	49,239	6.0	42,820	53,826	20.4
MRO (U.S.) ⁴	35,849	47,529	24.6	39,343	50,633	22.3
NPCC (U.S.).....	55,730	78,639	29.1	60,001	73,341	18.2
ReliabilityFirst ⁵	161,241	215,700	25.2	171,488	219,583	21.9
SERC.....	186,507	247,400	24.6	195,833	247,674	20.9
SPP.....	41,117	49,194	16.4	42,976	53,298	19.4
WECC (U.S.).....	122,881	152,467	19.4	124,924	161,358	22.6
Contiguous U.S.....	713,106	916,449	22.2	739,798	934,894	20.9
	2011			2012		
TRE (formerly ERCOT).....	63,532	73,075	13.1	64,947	74,733	13.1
FRCC.....	42,831	54,441	21.3	43,409	55,117	21.2
MRO (U.S.) ⁴	39,823	51,748	23.0	40,618	51,645	21.4
NPCC (U.S.).....	60,606	74,602	18.8	61,318	79,319	22.7
ReliabilityFirst ⁵	175,367	226,033	22.4	177,600	230,107	22.8
SERC.....	199,297	252,732	21.1	204,045	256,713	20.5
SPP.....	43,567	55,576	21.6	44,834	56,477	20.6
WECC (U.S.).....	126,318	170,649	26.0	127,495	176,431	27.7
Contiguous U.S.....	751,342	958,855	21.6	764,267	980,542	22.1
	2013			2014		
TRE (formerly ERCOT).....	66,514	75,435	11.8	67,655	76,191	11.2
FRCC.....	43,899	56,923	22.9	44,451	57,097	22.1
MRO (U.S.) ⁴	41,224	51,967	20.7	41,675	51,986	19.8
NPCC (U.S.).....	62,093	78,424	20.8	62,708	78,374	20.0
ReliabilityFirst ⁵	180,600	232,543	22.3	182,700	232,924	21.6
SERC.....	207,756	260,524	20.3	211,512	262,024	19.3
SPP.....	45,544	57,154	20.3	46,102	58,368	21.0
WECC (U.S.).....	127,459	179,803	29.1	130,302	181,327	28.1
Contiguous U.S.....	775,088	992,773	21.9	787,105	998,292	21.2

Source: U.S. Energy Information Administration/Electric Power Annual 2009

<http://www.eia.gov/cneaf/electricity/epa/epat4p3.html>

Appendix II : Excerpt from IMF’s Assumptions:

“A number of assumptions have been adopted for the projections presented in the World Economic Outlook. It has been assumed that real effective exchange rates remained constant at their average levels during February 8–March 8, 2011, except for the currencies participating in the European exchange rate mechanism II (ERM II), which are assumed to have remained constant in nominal terms relative to the euro; that established policies of national authorities will be maintained; that the average price of oil will be \$107.16 a barrel in 2011 and \$108.00 a barrel in 2012 and will remain unchanged in real terms over the

medium term; that the six-month London interbank offered rate (LIBOR) on U.S. dollar deposits will average 0.6 percent in 2011 and 0.9 percent in 2012; that the three-month euro deposit rate will average 1.7 percent in 2011 and 2.6 percent in 2012; and that the six-month Japanese yen deposit rate will yield on average 0.6 percent in 2011 and 0.3 percent in 2012. These are, of course, working hypotheses rather than forecasts, and the uncertainties surrounding them add to the margin of error that would in any event be involved in the projections. The estimates and projections are based on statistical information available through late March 2011.”

See: <http://www.imf.org/external/pubs/ft/weo/data/assump.htm> for full text

Appendix III : Extreme condition Test result: Indicated base gdp

1990	1991	1992	1993	1994	1995	1996	1997	1998
6,617.00	7,154.29	6,899.55	6,166.17	5,575.16	6,210.38	6,810.66	6,896.96	7,332.07

1999	2000	2001	2002	2003	2004	2005	2006	2007
7,654.13	5,656.05	5,236.61	5,951.63	7,263.30	8,564.22	10,265.25	12,228.65	14,443.46

2008	2009	2010	2011	2012	2013	2014	2015	Year
327.46	174.21	172.18	204.44	222.75	236.80	252.72	256.74	Indicated Base gdp (Bn\$)

Appendix IV: Equations

HYDRO SECTOR

Average Installation time hydro=

4

Units: Year

Average lifetime hydro=

30

Units: Year

becoming installed hydro=

construction complete hydro+maintenance and replacement investments

Units: mw/Year

capacity adjustment hydro=

Smooth N (Capacity gap/capacity adjustment time hydro,4,Capacity gap/capacity adjustment time hydro

,1)

Units: mw/Year

capacity adjustment time hydro=

2

Units: Year

capacity availability ratio=

Capacity margin/reference capacity margin

Units: dmn1

Capacity gap=

Max(0,desired capacity hydro-Hydro capacity installed- Hydro capacity under construction

)

Units: mw

Capacity margin=

1-"demand/supply ratio"

Units: dmn1

construction complete hydro= delay fixed (

investment rate hydro,Average Installation time hydro,investment rate hydro

)

Units: mw/Year

"demand/supply ratio"=

perceived maximum demand/total operating capacity

Units: dmn1

Depreciation hydro=

Hydro capacity installed/Average lifetime hydro

Units: mw/Year

desired capacity hydro=

weight of stated goal*stated goal hydro+(1-weight of stated goal)*desired hydro production

Units: mw

desired hydro production=

Min(perceived maximum demand,perceived performance of installed capacity hydro
)

Units: mw

effect of perceived demand on weight of goal= WITH LOOKUP (

relative perceived demand^elasticity of perceived demand on weight,

([(0,0)-(10,10)],(0,0.5),(0.5,0.7),(1,1),(2,1),(3,1))

Units: dmn1

elasticity of perceived demand on weight=

1

Units: dmn1

Hydro capacity installed= INTEG (

becoming installed hydro-Depreciation hydro,

1072)

Units: mw

Hydro capacity under construction= INTEG (

investment rate hydro-construction complete hydro,

0)

Units: mw

hydro potential remaining= INTEG (

-potential usage,

400)

Units: mw

initial perceived demand= INITIAL(

perceived maximum demand)

Units: mw

invest=

capacity adjustment hydro*investment start hydro

Units: mw/Year

investment rate hydro=

Min(invest,hydro potential remaining/time to use potential)

Units: mw/Year

investment start hydro=

PULSE TRAIN(2007, 1, 10, 2030)

Units: dmn1

maintenance and replacement investments=

Depreciation hydro+potential boost through upgrade

Units: mw/Year

perceived maximum demand=

Smooth N(estimated maximum demand,time to perceive peak demand,estimated maximum demand

,1)

Units: mw

perceived performance of installed capacity hydro=

Smooth N(total hydro operating capacity, 0.25, total hydro operating capacity

,1)

Units: mw

potential boost through upgrade=

upgrade fraction*Hydro capacity installed*upgrade time

Units: mw/Year

Note: At the full completion (March 3, 2006) of the Retrofit Project

(Akosombo hydro dam), the generation capacity increased significantly by 108mw, from 912mw to 1020. Maximum output when tested increased by 37%. Source VRA

potential usage=

construction complete hydro

Units: mw/Year

reference capacity margin=

0.25

Units: dmn1

relative perceived demand=

perceived maximum demand/initial perceived demand

Units: dmn1

stated goal hydro=

Max(total hydro operating capacity,perceived maximum demand)/capacity availability ratio

Units: mw

1580

time to use potential=

1

Units: Year

total hydro operating capacity=

Hydro capacity installed

Units: mw

total operating capacity=

total hydro operating capacity+total operating capacity rops

Units: mw

upgrade fraction=

0.1

Units: dmnl/Year

upgrade time=

PULSE TRAIN(2000,1,30, 2050)

Units: dmnl

weight of stated goal=

1*effect of perceived demand on weight of goal

Units: dmnl

DEMAND/SUPPLY SECTOR

Base GDP

Units: Bn \$

capacity availability ratio=

Capacity margin/reference capacity margin

Units: dmnl

change in consumption=

(indicated consumption-electricity consumption)/consumption time per year

Units: gw*hour/Year

change in reliability=

(indicated reliability-Supply reliability)/reliability adjustment time

Units: dmn/Year

consumption time per year=

1

Units: Year

desired electrification=

expected electricity coverage(Time)*effect of capacity availability on electrification

Units: dmn

effect of capacity availability on electrification= WITH LOOKUP (

capacity availability ratio,

(((1,0)-(4,10)),(-1,0),(0.5,0.6),(0.7,0.8),(1,0.9),(1.5,1),(2,1),(3,1))

)

Units: dmn

effect of capacity availability ratio on supply reliability(

[(-4,0)-(4,5),(-1.16208,0.1),(-0.501529,0.328947),(-0.0366972,0.526316),(0.525994

,0.855263),(1.11315,1.18421),(1.79817,1.40351),(2.72783,1.5)],(-1.16208,0.1

),(-0.501529,0.328947),(-0.0366972,0.526316),(0.525994,0.855263),(1.11315,1.18421

), (1.79817,1.40351),(2.72783,1.5))

Units: dmn

effect of electricity consumption on gdp (

[(0,0)-(12000,5),(1009.17,0.00193),(1957.19,0.131579),(2691.13,0.263158),(3853.21,0.592105),(4862.39,0.942982),(5596.33,1.18421),(6422.02,1.42544),(7247.71,1.60088),(7951.07,1.6886),(9051.99,1.71053)],(1009.17,0.00193),(1957.19,0.131579),(2691.13,0.263158),(3853.21,0.592105),(4862.39,0.942982),(5596.33,1.18421),(6422.02,1.44737),(7486.24,1.66667),(8954.13,1.79825),(10715.6,1.84211))

Units: dmnl

effect of price on demand=

relative price^elasticity on demand

Units: dmnl

effect of supply reliability on consumption(

[(0,0)-(2,2),(0.0183486,0.1),(0.250765,0.342105),(0.385321,0.578947),(0.452599,0.745614),(0.519878,0.894737),(0.605505,1.00877),(0.691131,1.12281),(0.850153,1.23684),(0.978593,1.29825),(1.20489,1.36842),(1.47401,1.39474)],(0.0183486,0.1),(0.250765,0.342105),(0.385321,0.578947),(0.452599,0.745614),(0.519878,0.894737),(0.605505,1.00877),(0.691131,1.12281),(0.83792,1.26316),(0.990826,1.35088),(1.19266,1.42982),(1.47401,1.47368))

Units: dmnl

elasticity of demand to commercial and industrial sector=

0.1

Units: dmnl

0.3

elasticity of demand to population=

0.711349

Units: dmnl

0.85

elasticity of domestic demand to pc gdp=

0.01

Units: dmn1

elasticity to electricity coverage=

0.187857

Units: dmn1

electricity consumption= INTEG (

change in consumption,

initial consumption)

Units: gw*hour

Electrification coverage= INTEG (

electrification rate,

0.3625)

Units: dmn1

electrification rate=

(desired electrification-Electrification coverage)/time to increase electrification

Units: dmn1/Year

estimated maximum demand=

initial peak demand*relative total demand

Units: mw

expected electricity coverage(

[(1990,0)-(2035,2)],(1990,0.48),(2000,0.66),(2010,0.8),(2020,1),(2030,1))

Units: dmnl

gdp per capita=

indicated base gdp/Population time series data

Units: Bn \$/people

indicated base gdp=

Smooth N(IF THEN ELSE(Time<2007, Base GDP, Base GDP*indicated effect of electricity consumption on gdp),0.25,Base GDP,1)

Units: Bn \$

indicated consumption=

effect of supply reliability on consumption(Supply reliability)*initial consumption
*effect of price on demand

Units: gw*hour

indicated effect of electricity consumption on gdp=

Delay N(effect of electricity consumption on gdp(electricity consumption), 1,effect of electricity consumption on gdp(electricity consumption),3)

Units: dmnl

indicated reliability=

effect of capacity availability ratio on supply reliability(capacity availability ratio)*initial reliability

Units: dmnl

inital gdp per capita= INITIAL(

gdp per capita)

Units: Bn \$/people

initial consumption=

initial peak demand*total hours in a year*megawatt to gigawatt converter

Units: gw*hour

initial electricity coverage= INITIAL(

Electrification coverage)

Units: dmn1

initial GDP= INITIAL(

indicated base gdp)

Units: Bn \$

initial peak demand= INITIAL(

"Maximum peak generation/demand (mw)")

Units: mw

initial population= INITIAL(

Population time series data)

Units: people

initial reliability= INITIAL(

Supply reliability)

Units: dmn1

megawatt to gigawatt converter=

0.001

Units: gw/mw

perceived maximum demand=

Smooth N(estimated maximum demand,time to perceive peak demand,estimated maximum demand

,1)

Units: mw

Population time series data

Units: people

World Development indicators

relative commercial and industrial demand=

relative gdp^elasticity of demand to commercial and industrial sector

Units: dmn1

relative domestic demand=

relative gdp per capita^elasticity of domestic demand to pc gdp*relative urban population

^elasticity of demand to population*

relative electricity coverage^elasticity to electricity coverage

Units: dmn1

relative electricity coverage=

Electrification coverage/initial electricity coverage

Units: dmn1

relative gdp=

indicated base gdp/initial GDP

Units: dmn1

relative gdp per capita=

gdp per capita/initial gdp per capita

Units: dmnl

relative total demand=

relative commercial and industrial demand*relative domestic demand

Units: dmnl

relative urban population=

Population time series data/initial population

Units: dmnl

reliability adjustment time=

1

Units: Year

Supply reliability= INTEG (

change in reliability,

0.5)

Units: dmnl

time to increase electrification=

1

Units: Year

time to perceive peak demand=

0.25

Units: Year

total hours in a year=

$$24 * 365.25$$

Units: hour

REST OF POWER SECTOR

average construction time=

$$2$$

Units: Year

average life time=

$$20$$

Units: Year

becoming complete rops= delay fixed (

$$\text{capacity construction rops, average construction time, 0})$$

Units: mw/Year

becoming installed rops=

$$\text{becoming complete rops} + \text{maintenance and replacement investment rops}$$

Units: mw/Year

capacity adjustment rops=

$$\text{Smooth N}(\text{capacity gap rops} / \text{time to adjust capacity rops}, 2, \text{capacity gap rops} / \text{time to adjust capacity rops}, 1)$$

Units: mw/Year

capacity availability ratio=

$$\text{Capacity margin} / \text{reference capacity margin}$$

Units: dmnl

capacity construction rops=

$\text{Min}(\text{Potential capacity rops}/\text{time to use potential rops}, \text{investment rops})$

Units: mw/Year

capacity gap rops=

$\text{Max}(0, \text{desired capacity rops} - \text{Capacity under construction rops} - \text{Installed capacity rops})$

Units: mw

Capacity under construction rops= INTEG (

capacity construction rops-becoming complete rops,

0)

Units: mw

capacity usage rops=

becoming complete rops

Units: mw/Year

depreciation rops=

$\text{Installed capacity rops}/\text{average life time}$

Units: mw/Year

desired capacity rops=

$(\text{weight of stated goal} * \text{goal for rops} + (1 - \text{weight of stated goal}) * \text{maximum production rops})$

$* \text{effect of capacity availability ratio on desired capacity rops}$

Units: mw

desired production rops=

Smooth N(total operating capacity rops,1,total operating capacity rops,1)

Units: mw

effect of capacity availability ratio on desired capacity rops=

IF THEN ELSE(capacity availability ratio>2, 0, 1)

Units: dmn1

effect of price on supply=

relative price^elasticity on supply

Units: dmn1

goal for rops=

(Max(total operating capacity rops,perceived maximum demand)/capacity availability ratio

)*effect of price on supply

-IF THEN ELSE

(Time<2010, 0, Hydro capacity installed

)

Units: mw

Hydro capacity installed= INTEG (

becoming installed hydro-Depreciation hydro,

1072)

Units: mw

initial capacity rops=

0

Units: mw

Installed capacity rops= INTEG (
becoming installed rops-depreciation rops,
initial capacity rops)

Units: mw

investment rops=
capacity adjustment rops*investment start rops

Units: mw/Year

investment start rops=
PULSE TRAIN(2006, 1, 20, 2030)

Units: dmdl

start at 2004

maintenance and replacement investment rops=
depreciation rops

Units: mw/Year

maximum production rops=
Min(desired production rops,perceived maximum demand)

Units: mw

perceived maximum demand=
Smooth N(estimated maximum demand,time to perceive peak demand,estimated
maximum demand
,1)

Units: mw

Potential capacity rops= INTEG (
-capacity usage rops,

20000)

Units: mw

Note: 42,727MW South Africa's installed capacity as at 2009 source IEA, (South Africa's population is about 2times Ghana's, so 20000mw for Ghana will suffice

time to adjust capacity rops=

2

Units: Year

time to use potential rops=

1

Units: Year

total operating capacity rops=

IF THEN ELSE(Time<2000,Installed capacity rops, Installed capacity rops)

Units: mw

weight of stated goal=

1*effect of perceived demand on weight of goal

Units: dmnl

COST AND PRICE STRUCTURE

"average operating/maintenace cost per mw"=

2

Units: Ghc/mw

capacity availability ratio=

Capacity margin/reference capacity margin

Units: dmnl

change in cost structure=

(operating cost-operating cost structure)*effect of capacity availability ratio on indicated price

/cost adjustment time

Units: Ghc/Year

change in price=

(indicated price-Price)/price adjustment time

Units: Ghc/Year

cost adjustment time=

1

Units: Year

effect of capacity availability ratio on indicated price= WITH LOOKUP (

capacity availability ratio,

([(0,0)-(4,10)],(0.5,1),(1,1),(2,1.3),(3,1.5))

Units: dmn1

effect of price on demand=

relative price^elasticity on demand

Units: dmn1

effect of price on supply=

relative price^elasticity on supply

Units: dmn1

effect of relative cost on indicated price=

relative operating cost^elasticity of price to cost

Units: dmn1

elasticity of price to cost=

1

Units: dmn1

elasticity on demand=

-0.1

Units: dmn1

elasticity on supply=

1

Units: dmn1

indicated price=

initial price*effect of relative cost on indicated price

Units: Ghc

initial operating cost= INITIAL(

operating cost structure)

Units: Ghc

initial price= INITIAL(

Price)

Units: Ghc

operating cost=

"average operating/maintenace cost per mw"*total operating capacity

Units: Ghc

operating cost structure= INTEG (
change in cost structure,
2373)

Units: Ghc

Price= INTEG (
change in price,
1)

Units: Ghc

price adjustment time=
1

Units: Year

reference price= INITIAL(
Price)

Units: Ghc

relative operating cost=
operating cost structure/initial operating cost

Units: dmn1

relative price=
Price/reference price

Units: dmn1

total operating capacity=
total hydro operating capacity+total operating capacity rops

Units: mw