Smart Electricity Grid with Real Time Pricing (RTP): An Alternative to Fixed Electricity Pricing In the Ghana Electricity Market.

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Abstract

Electricity pricing has been identified as a major cause of the shortfall in power supply in Ghana. End user electricity prices are fixed for long period and do not reflect the marginal cost of generating electricity with a shift from hydro supply to thermal supply. Time varying electricity pricing (Real Time Pricing) RTP where retail electricity prices vary in real time is an alternative proposition to the fixed pricing system. This system ensures that supply is always equal to demand through a constant variation in price during peak and off peak periods with advanced metering systems that sends signals to consumers to alert them during periods of high prices and periods of low prices.

A simulation model based on system dynamics methodology is developed to analyze the causal relationships between price variation and supply demand response. The central focus of the model is the price that is used to reason about the behavior of demand and supply in the electricity market of Ghana given different pricing mechanism. The model is further used to investigate the welfare benefits consumers and producers would drive with the implementation of a real time pricing system.

The results of the study shows that RTP can be an effective mechanism to meet peak loads as prices are adjusted in real time to cover the cost of electricity supply. It also provides substantial benefits to electricity producers by reducing the cost of capital investment and operations and maintenance cost. The study however observed that to maximize the benefits to consumers there is the need to shift from cost intensive sources of electricity supply such as gas powered thermal plants to cheaper renewable sources of electricity with storage units that would serve as backup systems.

Keywords: *Real Time Pricing, Electricity, System Dynamics*

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1. Introduction

In the last two decades, Ghana has experienced a significant increase in electricity consumption with a growth of 10-15% per annum. The continuous increase in electricity demand is a direct result of economic transformation driven by expanding industrial and service sector activities, massive urbanization, growth in population and income and government national electrification scheme. Between 2000 and 2013, the country experienced a 46% increase in electricity consumption with an economic growth rate of about 7.6% per annum (World Bank Data). Electricity supply has however failed to match the increasing demand. Between 2000 and 2009, the installed generation capacity grew by only 7%. With demand continuously exceeding supply, the country in the last decade has been experiencing frequent power outages (load shedding). Residential and commercial consumers experience up to 24 hours of blackouts and 12 hours of supply with industrial consumers experiencing between 6 to 12 hours of power cut. The country sheds between 400-700MW of power during off-peak and peak periods because of the worsening demand supply gap (Power Africa 2014). The frequent power outages have resulted in a slowdown in industrial activities, jobs and income losses and a disincentive to foreign investors. The institute of statistical, social, and economic research (ISSER) in 2014 estimated an annual loss of between $320million and $924million in productivity and economic growth that translate to 2% to 6% of GDP due to electric power outages.

Electric power is an important factor in the economic development of countries across the world. It is a key determinate of the quality and standard of living of a population. Industrial production and small-scale businesses have become heavily reliant on electric power. Sectors such as education, health, manufacturing, mining, construction, entertainment, and communication significantly depend on electricity for their activities. Without a safe, sustained, reliable, and reasonably affordable supply of electricity to meet demand, a country can hardly make progress in its economic and social development (ISSER 2005).

Electricity pricing has been identified as a major cause of the demand supply gap in the power sector. End user electricity prices are too low and are fixed for a much longer period with a quarterly or annual review and do not reflect generation costs with a shift from the relatively cheaper hydro to gas and light crude oil. The focus of this project is to examine the current pricing mechanism against an alternative pricing scheme in the form of real time pricing. Other related causes of this problem that is not the focus for this thesis include unfunded and weak targeted subsidies to consumers, power theft and nonpayment of utility bills. These have harmed the financial health of the Electricity utility providers (Joe Amoako Tuffour et al, 2015). The low prices have been a disincentive to local and foreign private investors in the generation sector. A higher price that is equal to or above the marginal cost of generating electricity could have been an appropriate option to attract private investors to help reduce the demand supply gap. However higher prices would deprive most household consumers of electricity since they cannot afford to pay. While low prices are directly beneficial to poor people, blackouts are problematic, and so is the economic inefficiency of the entire electricity system that follows from regulated prices.

An alternative pricing mechanism that has been adopted by other countries to address the shortfall in electricity supply is time varying electricity pricing. This system ensures that supply is always equal to demand through a constant variation in price in real time with advanced metering systems that send signals to consumers to alert them during periods of high prices and periods of low prices. This system maximizes benefits for both producers and consumers of electricity. Prices are high during peak demand periods when expensive sources of generation are used. Inversely prices will be low during off peak periods. This affords consumers the opportunity to buy electricity at a cheaper price and to reduce consumption when prices are high.

This project therefore seeks to analyze the welfare effects of consumers and producers and the favourability or otherwise of a Real Time Pricing (RTP) system where retail electricity prices vary frequently, usually hourly or minute-by-minute intervals to reflect the changing supply/demand imbalance (Severin Borenstein). Thus, the thesis analyses a radical shift in pricing system to a system that is only at the test level in developed countries. Hence, if the thesis analyses a pricing system that is more advanced than what is typically used in developing countries, implementation could only happen some years into the future. The thesis also introduces the concept of electricity storage where electricity can be bought and stored in batteries or hydro electric reservoirs when prices are low during off peak periods and sold when prices are high during peak periods.

As identified earlier, one of the major challenges facing the electricity sector is tariffs that are always below the marginal cost of generating electricity. Fixed electricity pricing creates economic inefficiencies (Newell.S & Faruqui.A 2009). During periods of peak demand consumers pay a price much lower than the cost of generation as expensive thermal plants that run on gas or Light Crude Oil (LCO) are connected to the grid. However, during off peak hours consumers tend to pay more for electricity since power supplied is mainly from hydro plants that are relatively cheaper.

The implementation of an Automatic Adjustment Formula (AAF) for electricity tariff adjustment was proposed in 2002. The main objective of the AAF was to review quarterly, electricity tariffs to reflect changes in factors whose effects on operations were considered beyond the control of the utility companies (PURC annual report 2011). This new tariff adjustment formulation became operational in 2011 but has not been fully implemented due to government interference in the price setting mechanism. Government often promises to absorb the price mark-up instead of passing it onto the consumer but delays in paying the distributors these subsidies (Africa Economics & IMANI, 2014).

Existing literature on electric power in Ghana are mostly focused on investigating generation challenges facing the power sector and the negative effect of frequent power outages on the national economy mostly using regression or econometrics techniques. Philip Kofi Adom (2013) used the rolling regression technique to investigate how the effects of income, economic structure, and industry efficiency on aggregate electricity demand vary with time. Ackah.I et al (2014) used the structural time series model to study the impact of economic and non-economic factors on electricity demand in Ghana. Batinga.B (2015) used system dynamics methodology to study the structure and causal relationship between electricity pricing and investment in new generation capacity. Teye.E (2011) applied system dynamics to understand the nexus between electric power demand and economic growth. There is no current literature that examines time varying pricing in the electricity market in Ghana. William W. Hogan, Severin Borenstein, Ahmad Faraqui and Samuel Newell have written extensively on the efficiency and fairness of real time electricity pricing in retail electricity market in the United States and the Nordic countries.

With RTP, prices of electricity will vary frequently to reflect supply demand balances and cost of generation. During peak or off-peak periods, prices will be automatically adjusted to meet marginal cost of generation and consumers can choose when to consume electric power.

The questions to be addressed in this project include:

How would RTP affect the supply and consumption of electric power?

Secondly, how would a shift from fixed price to RTP affect the welfare of consumers? Will poor consumers suffer because prices will always be higher than with subsidized prices? Alternatively, are poor consumers sufficiently flexible that they can benefit from periods with very low prices? Or, will more rapid economic growth and more money for governmental welfare programs benefit the poor?

Finally, how would RTP contribute to the optimal utilization of available generation resources?

To address the specific issues a simulation model based on system dynamics methodology is used to analyze the working of RTP.

The simulation results show that with the implementation of RTP, the problem of blackouts will be eliminated with supply matching demand at all times through real time adjustment of price to reflect the cost of generating electricity and to a larger extent control the level of peak electricity consumption. The results show increase in electricity consumption when price is low and decrease in consumption when price is high. Suppliers on the other hand are able to meet demand with a fair retail price reflecting their marginal production cost. Consumer welfare experience significant increase with the implementation of RTP as consumers would pay lower prices during off peak periods. The results also show an efficient utilization of available resources with producers not having to build additional production capacity. Producers also experience a reduction in their variable operating and maintenance cost with a reduction in peak demand. In terms of future capacity investment decisions the results indicate that investing in renewable sources in the form of solar PV with specific reference to Ghana, together with electricity storage systems is the most cost effective and surest way of providing electricity to a majority of the population at lower prices.

The thesis proceeds by analyzing the theoretical background for the adoption of this policy option. This is followed by an examination of the existing structure of the electricity market in Ghana. The next section is a detailed description of the structural relationships underlying the proposed policy using a system dynamics model. This is followed by the model validation and the assumptions made in the model. The thesis further analyzes the behavior generated by this structure with particular emphasis on pricing, supply, demand, and welfare of both consumers and producers. The preceding section discusses the implementation issues related to the adoption of RTP. The final section looks at various discussions and conclusions that can be drawn from the policy option.

2. Background/theory

The twenty-first century has witnessed a significant growth in energy demand for industrial and domestic purposes. This has led to major policy reforms in the electric power sector across the world. Most developed countries are shifting from coal and fuel power generating systems to renewable energy resources popularly known as green energy. The sole aim of this shift is to address climate issues by reducing carbon emissions into the atmosphere and to address growing demand for electric power by ensuring an efficient, secured, reliable, and cost effective supply of electric power. This has led to the adoption of the smart electricity grid in most advanced countries such as the United States, Europe, Australia, and Asia. A smart electricity grid uses information and communication technology to connect electricity supply utilities with consumers. The system allows the electricity grid to respond to demand and market conditions, reconfigure automatically to prevent system shutdown or restore outages. The system uses a two-way communication system with smart meters (advanced metering infrastructure) that sends electricity price and load information to consumers at time intervals and receive consumer response. This gives consumers an opportunity to reduce or shift consumption during peak periods in response to time based rates. This system works effectively with time-based pricing schemes such as real time pricing, time of use pricing or critical peak pricing that are collectively referred to as dynamic pricing.

The concept of dynamic pricing (real time pricing) of electricity where retail electricity prices closely reflect variations in the marginal cost of generating electricity has been around for the last 60 years. The marginal cost of electricity changes frequently over time because of constant fluctuation in demand and the inability to store electricity resulting in capacity constraints and excesses during peak and off peak demand periods. To ensure economic efficiency and financial viability, the amount of electricity generated should be equal to the demand at all times. The economic principle of RTP adoption is that when retail price of electricity is high at a given time consumers will conserve electricity and when price is low in a given time consumers will increase their electricity consumption. Since demand is highly variable there will be times when there is excess capacity during off peak period and the cost of producing electricity will be the operating and maintenance costs and cost of fuel for non-renewable technologies such as thermal plants. However, during peak demand period capacity is constricted resulting in a further increase in generation cost and an increase in wholesale market price. Wholesale market price in most developed countries vary by the hour, however the retail price are mostly constant over long periods which do not reflect the variations in wholesale cost of electricity. In most developing countries retail electricity pricing and liberalizing electricity markets to competition has been a daunting challenge for policy makers. There are external pressures for the removal of electricity subsidies and higher tariffs that reflect the cost of generating electricity and the creation of a market based on competitive prices. On the other hand, there is internal resistance to such policies from consumers who feel that electricity has become a necessity and should be met at a minimum cost. The pricing of electricity in developing countries is therefore subject to social policy programmes, economic down turns and political objectives whether or not the prices reflect the full cost of generating electricity.

3. Ghana's Electricity market

The electricity market of Ghana consist of a retail (regulated) market and a contract (deregulated) market. The generation sector is largely dominated by the state owned generating firm Volta River Authority (VRA), Bui Power Authority and other Independent Power Producers (IPP). Currently, 88% of generation capacity is owned and operated by the public sector with IPP contributing about 12% of the available generation capacity. Transmission and distribution services are fully state-owned. The retail market constitutes the distribution companies; the Electricity Company of Ghana (ECG) and the Northern electricity distribution company (NEDCO) which are fully state owned. The electricity company of Ghana is a stated owned company, which is the premier retailer and distributor of electricity in the seven southern regions of the country. NEDCO is a subsidiary of the state owned VRA that distribute electric power to the three northern regions of the country. Transmission is the sole responsibility of the Ghana grid company limited (GRIDCO). The contract buyers are mainly large industries like mining firms and aluminum smelting industries. Electricity pricing for the retail market is set by a state regulated agency; the Public Utility regulatory commission (PURC) and are reviewed quarterly or annually. The contract market prices are determined through a bilateral agreement between the producers of electricity and the individual buying firms. The electricity regulations act 2008 LI 1937 sought to establish a wholesale electricity market which will consist of a spot market and a bilateral contract where the spot market price for electricity shall be based on the system marginal cost of supply and merit-order dispatch. This regulation is yet to be implemented. In 1995, the government initiated the power sector reform programme aimed at improving the financial and operational efficiency and performance of electricity utilities and to create an enabling environment for private sector participation in the sector. These reforms have however not been fully implemented as the distribution and transmission firms are still fully owned by the government without any private sector participation.

3.1 Regulatory agencies

Two state institutions established by acts of parliament regulate the Ghana electricity market. These are the Energy Commission and the Public Utilities Regulatory Commission (PURC). The Energy Commission was established by the Energy Commission's Act 1997 (Act 541). The commission serves as the technical regulator and its core mandate is to regulate and manage the development and utilization of energy resources in Ghana as well as to provide the legal, regulatory, and supervisory framework for all providers of energy in the country. The commission's functions in relation to the power sector are to prescribe standards of performance, technical and operational rules of practice for the supply, distribution, and sale of electricity to consumers by public utilities. It is also responsible for licensing public utilities for the transmission, wholesale supply, distribution, and sale of electricity. The PURC serves as the economic regulator. It was established under the PURC act 1997 act 538 as part of the utility sector reform process to regulate the provision of utility services and to provide guidelines on rates chargeable for the provision of utility services. The commission is responsible for setting and approving electricity tariffs in accordance with the tariff guidelines established by the commission itself.

3.2 Electricity tariff structure

Retail electricity consumers in Ghana such as residential and commercial consumers pay electricity prices that are fixed for a long period mostly a year. The final end user tariff is calculated as the sum of the bulk generation tariff, transmission, and distribution service charge. The bulk generation tariff is the generation component of the tariff at which distribution utilities sell electricity to customers in the regulated market. It is calculated as the weighted average of the price of hydro generation and the market price of thermal complement. The bulk generation tariff is aimed at recovering the operation and maintenance cost, cost of fuel input and return on capital investment over the long term. Transmission and distribution service charges are paid to the electricity transmission and distribution utilities to cover the cost of providing transmission and distribution services to regulated customers. The transmission and distribution service charges are set based on annuity of replacement value of transmission and distribution assets, operations and maintenance cost, standard system losses, capital adjustment factor, average annual inflation and productivity factor. Consumers are also charged a fee to cover the cost of meter reading and billing. These service cost components are adjusted annually. Tariffs are also subsidized for low-income earners under the lifeline supply concept, which seeks to provide a certain quantity of electricity at a low rate.

3.3 Supply/demand of electricity

Electricity supply in Ghana is primarily from hydro and thermal power plants. Current installed generation capacity stands at 3174MW comprising 50.86% hydro, 49.1% thermal and 0.04% solar photovoltaic (PV) with an average dependable capacity factor of 88% (Energy Commission Report, April 2016). 87% of the installed generation capacity is state owned with the remaining 13% owned and operated by Independent Power Producers (IPPs). The generation of electricity is largely influenced by availability of water in the hydro dams and the availability and cost of natural gas and Light Crude Oil (LCO). The supply of electricity has been saddled by a high generation cost in the form of fuel cost, which is not fully covered by the current fixed retail tariff. The country is endowed with a huge potential of renewable resources in the form of solar and wind power which have not been exploited.

Electricity demand in Ghana is estimated to be growing at a rate of 10-12% per annum. This growth rate is largely due to the rapid growth in population, increased economic activities and growth in income. Electricity demand has been categorized into residential, commercial, and industrial demand. Industrial demand for electricity accounts for about 47% of the total national electricity demand with residential and commercial sectors accounting for 39% and 14% respectively. Residential electricity demand is largely driven by increased use of electric appliances such as refrigerators, electric heaters, home electronics, and kitchen gadgets for the purpose of heating, entertainment, cooking and preserving food (IEA 2004). Industrial and commercial sector demand is a result of modern day use of computers to perform office work, air conditioners for cooling, lightening and to operate equipment for the production of goods. Economic growth has been a major driving force for the continuous increase in power demand. Albert Lemma et al 2016 for instance found a positive correlation between electricity consumption and economic growth indicating an increase in electricity consumption with increasing economic growth. With an average economic growth rate of 7.31% per year (data.worldbank.org/country/Ghana retrieved 31/10/2016) in the last 7 years, the country has witnessed a corresponding increase in electricity consumption. Electricity demand has been affected by the price of electricity relative to other forms of energy. Individual households cut down their consumption when prices are adjusted higher. This reduction comes in the form of using energy efficient appliances, switching off lights and electric gargets when not in use or saving electricity by using other forms of energy such as gas for cooking. Growth in income is another driving force for the increase in electricity demand. An increase in income increases consumer's purchasing power and they tend to acquire more electric using gargets. Ishmeal ackah et al 2014 found that income elasticity of demand is highly elastic as a 1% rise in income leads to a 0.7% increase in electricity demand.

4. The model

The model design is inspired by the economic principle of how price, demand and supply interact. The central focus of the model is the price which is used to reason about the behavior of demand and supply in the electricity market of Ghana given different pricing mechanism. The model is further used to investigate the welfare benefits consumers and producers would drive with the implementation of a real time pricing system. The main objective of the model design is to test different policy scenarios for the future with particular emphasis on the price and the feasibility of electricity storage systems in the form of batteries and pumped hydro storage and also to investigate which generating technologies are economically efficient to invest in the future. The model comprises of 5 main sectors. These include the pricing, demand, supply and inventory sectors. The fifth sector is dedicated to the calculation of consumer and producer benefits and therefore does not have any feedback effect on the main model. The time unit in the model is set to minutes over 7 days with a DT of 1 and RK4 integration method. The various sectors of the model are represented in the diagram.

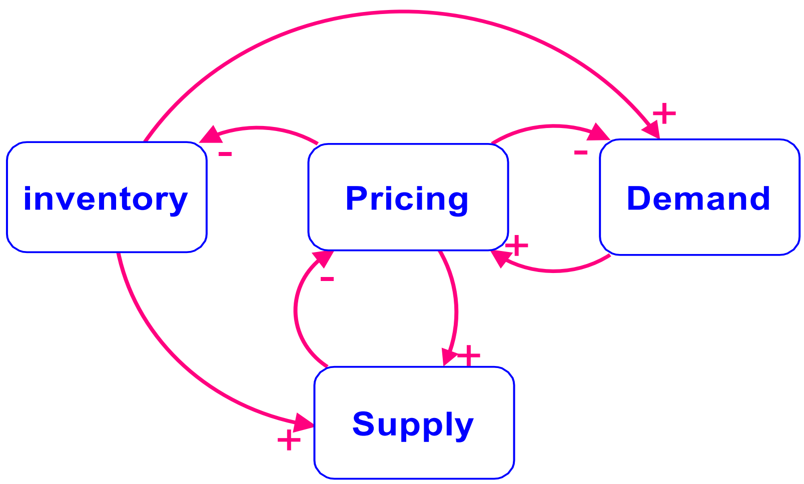

Figure 1. An Overview of model structure and Causal links

The above diagram illustrates a simplified version of the model structure showing the causal relationships between the various sectors of the model. The price is at the center of the model that has a direct effect on the other sectors. The model shows a balancing feedback loop between price and supply and price and demand. It indicates that a higher price leads to an increase in supply that over time results in a fall in price. A price increase on the other hand results in a fall in demand that over time results in a fall in price. The price affects inventory in two ways. First inventory holders will buy electricity when the price is low and sell when the price is high. A low price therefore builds up the inventory and a high price depletes the inventory. Both demand and supply are affected positively by the inventory.

4.1 Modeling Price

Price is the central focus of this model that changes instantaneously and builds on the expected price in response to demand/supply balances. Price in this model has two components. The first component is the fixed price that represents the traditional price that consumers are actually paying for every Kwh of electricity consumed. The fixed price used in the model is an average price of all the tariff categories as consumers in different consumption levels pay different tariffs. The second component is the real time pricing which represent the future pricing policy option. The electricity price is formulated as follows.

$$P = EP * (1 + PS * (DS - 1)) \quad (1)$$

$$P = FP \quad (2)$$

$$EP(t) = EP_{t-dt} + (\Delta EP)*dt \quad (3)$$

$$\Delta EP = (P - EP)/AT \quad (4)$$

$$DS = td/ts \quad (5)$$

Where P is the price, EP is the expected price, PS is price sensitivity, DS is demand/supply ratio, and FP is fixed price. EP_{t-dt} is the expected price at a previous time, *td* is total demand, *ts* is total supply and AT is the time to adjust expected price. The price is anchored to the expected price, which in turn is adjusted to the price through a first order positive feedback process with an adjustment time of 30 minutes. The price increases or decreases in response to demand supply balance and price sensitivity. In Ghana the price sensitivity is 1 as electricity prices are mostly fixed for long periods and do not change with changes in demand or supply. Change in expected price represents the gap between price and expected price over the adjustment time. The DS is simply expressed as demand over supply. A ratio greater than 1 implies that demand exceeds supply resulting in an increase in price. On the other hand, a ratio less than 1 implies demand is less than supply resulting in a fall in price.

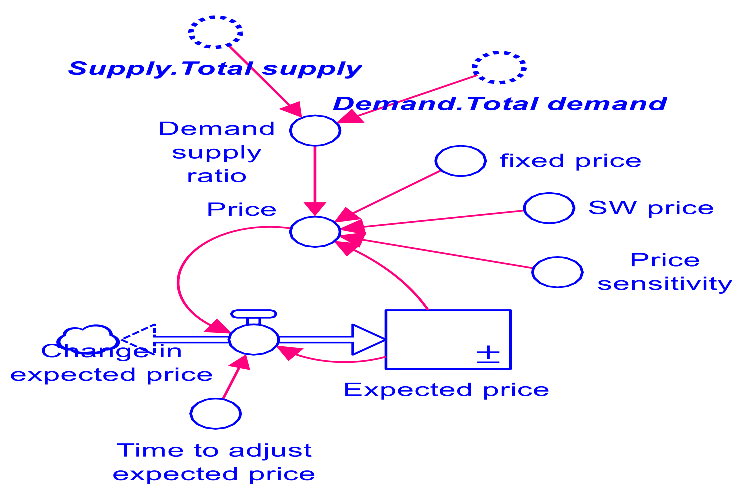

Figure 2.Stock and flow structure of Price Sector

The diagram above represents the structure of the pricing sector in the model. Two different price mechanism are run and tested in the model using the *"SW price"* (switch) variable. When the switch variable is zero the model runs with the fixed price and when it is one the model runs with the real time pricing (variable price).

4.2 Modeling supply

The supply sector comprises of the current generating sources available in Ghana in the form of hydro power plants and thermal that is powered by natural gas or light crude oil. Solar PV is a huge potential source of electricity generation that has not been fully exploited yet with only 2 MW of capacity currently available. Solar PV is therefore represented in the model as an alternative to current sources of generation in the future. Though solar energy is not always available throughout the day, it is worth noting that with the rapid development of new technologies in the form of large storage batteries, power can be generated during the day and stored for later use when the sun is not available. The stock and flow structure of the supply sector is represented in the figure below.

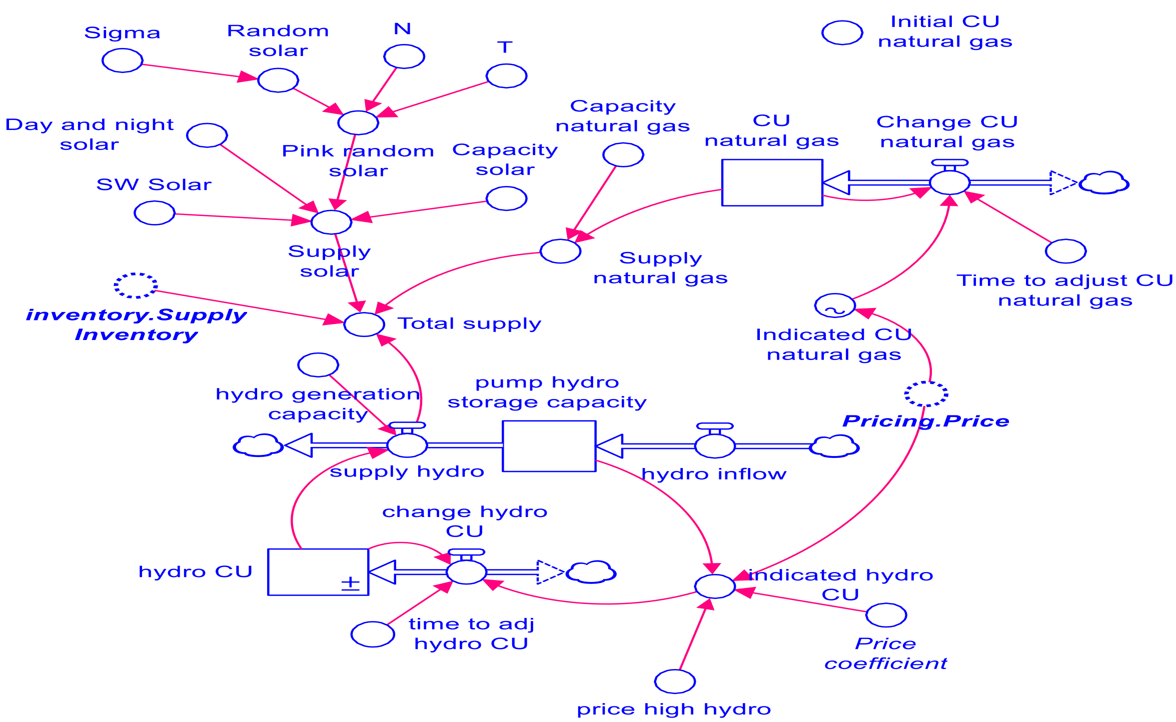

Figure 3. Stock and Flow structure of Supply Sector

Total supply is the sum of electricity supplied from all generating units and storage facilities available. Total supply is represented as

$$Total\_supply = Supply\_natural\_gas + Supply\_solar + Supply\_Inventory + hydro\_Supply \quad (6)$$

The model assumes a constant generation capacity for all the generating units as such the only variable that changes in response to variations in price given the marginal cost of generation for each utility is the capacity utilization. The CU for both NG and hydro are influenced by price and are formulated as a first order balancing feedback process that is adjusted to the indicated capacity utilization. The CU is represented as a stock that accumulates the change in CU for both NG and hydro. This is expressed in the equation below.

$$CU\_natural\_gas(t) = CU\_natural\_gas(t - dt) + (Change\_CU\_natural\_gas) * dt \quad (7)$$

$$Change\ CU\ natural\ gas = (Indicated\ CU\ natural\ gas - CU\ natural\ gas)/ Time\ to\ adjust\ CU\ natural\ gas \quad (8)$$

Change in CU natural gas is the rate at which the CU changes in response to changes in price. It is formulated as the difference in the current capacity utilization and the indicated capacity utilization over the adjustment time. The time to adjust the CU is set to 30 minutes to reflect the quick variation in price. The graph below represent the nonlinear graphical function of the indicated capacity utilization.

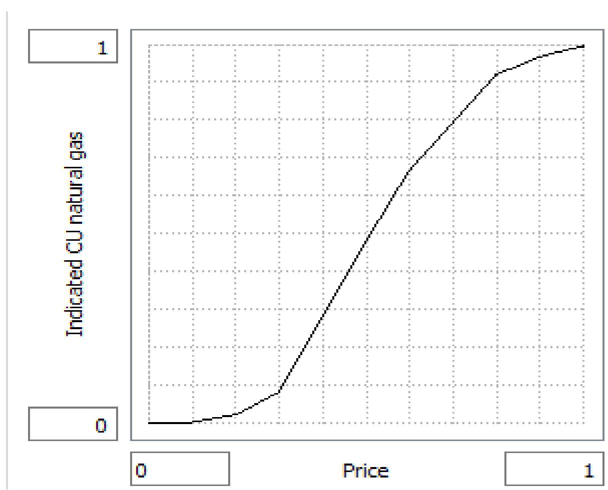

Figure 4.Nonlinear Graphical Function for Indicated CU

The indicated CU for NG is modeled as a nonlinear function that increases with an increase in price and vice versa. Since different operators of NG plants incur different levels of marginal cost, their rate of CU is adjusted by the price level. The graph represents the different marginal cost of the producers. A high price above the marginal cost results in higher CU and vice versa. This formulation is adopted, as it is difficult to estimate the marginal cost of different producers.

The amount of electricity supplied from natural gas is captured in the expression below.

$$Supply\,natural\,gas\;=\;Capacity\,natural\,gas * CU\,natural\,gas \qquad (9)$$

With a fixed installed capacity for natural gas at 19 MWh/minute, the electricity supply from natural gas is mainly determined by the capacity utilization of natural gas that is determined by the cost of gas or light crude oil and the price of electricity depicted in the nonlinear graph above.

Supply from hydro is represented as a reservoir that stores water in the form of energy during off peak periods and discharges water for generating electricity during peak periods. The model assumes a constant inflow rate of 9000 MWh/day of energy and an outflow that is determined by how much electricity the operator is willing to generate given the available capacity and the price. Pumped hydro storage capacity is represented as a stock, which accumulates the difference between the hydro inflow and the hydro supply. Hydro supply is formulated as,

$$Hydro\,Supply\;=\;hydro\,generation\,capacity * hydro\,CU \qquad (10)$$

Hydro supply is the amount of electricity supplied from hydro plants. It acts as an outflow and depletes the reservoir as more electricity is generated. The amount of electricity supplied from the reservoir is determined by the available capacity and the rate of capacity utilization. The available capacity for hydro is constant at 18 MWh per minute representing the minimum capacity needed to meet the electricity needs of the country every minute.

Hydro CU is represented as a stock that is adjusted to the indicated hydro CU in a first order control system. The flow to the stock "change in hydro CU" is formulated as

$$change\_hydro\_CU\;=\;(indicated\_hydro\_CU - hydro\_CU)/time\_to\_adj\_hydro\_CU \qquad (11)$$

$$indicated\_hydro\_CU = (IF\ pump\_hydro\_storage\_capacity > 0\ THEN\ MIN\ (1, MAX\ (0, (Price - price\_high\_hydro)/Price\_coefficient))\ ELSE\ 0) \quad (12)$$

The indicated hydro CU is a function of electricity price and the amount of water in the reservoir. The producers of hydropower will only generate electricity when there is water in the reservoir and when the electricity price is above the price high set for hydro. The price high for hydro is the minimum price at which operators of hydro plants are willing to generate power. When the electricity price is below the price high no power is generated.

Electricity supply from solar PV is modeled differently from natural gas and hydro. Energy generated from solar plants is mainly determined by the availability of sun and cloud cover during the day that defines the rate of capacity utilization of solar plants. Electricity supply from solar in this model is formulated as

$$Supply\_solar = SW\_Solar * Capacity\_solar * MAX\ (0, Day\_and\_night\_solar + pink\_random\_solar) \quad (13)$$

The available solar capacity just as natural gas and hydro is assumed to be fixed. Solar supply is expressed as a function of the available solar capacity and the amount of sunlight received during the day. The “SW Solar” variable is used to activate or deactivate the solar sector in the model by changing the value to 1 to activate and 0 to deactivate.

$$Day\_and\_night\_solar = SIN\ (2 * PI * TIME/\ (60 * 24)) \quad (14)$$

Day and night solar is formulated with the sin wave function, which represents the availability of sun during the day.

$$pink\_random\_solar = SMTHN\ (Random\_solar, time\_of\_daylight, N) \quad (15)$$

Since the production of solar power does not vary quickly as compared to variations in cloud cover, there is the need to smoothen out the frequent variations in cloud cover. This is expressed in the pink random solar which is used to get a somewhat smooth variation in cloud cover. This is formulated with the SMTHN function with an N^{TH} order and the time of daylight(T).

4.3 Modeling demand

The model assumes frequent variation in electricity demand over the day. Demand is therefore formulated to investigate the response of consumers to changes in price. The demand sector is represented in the figure below

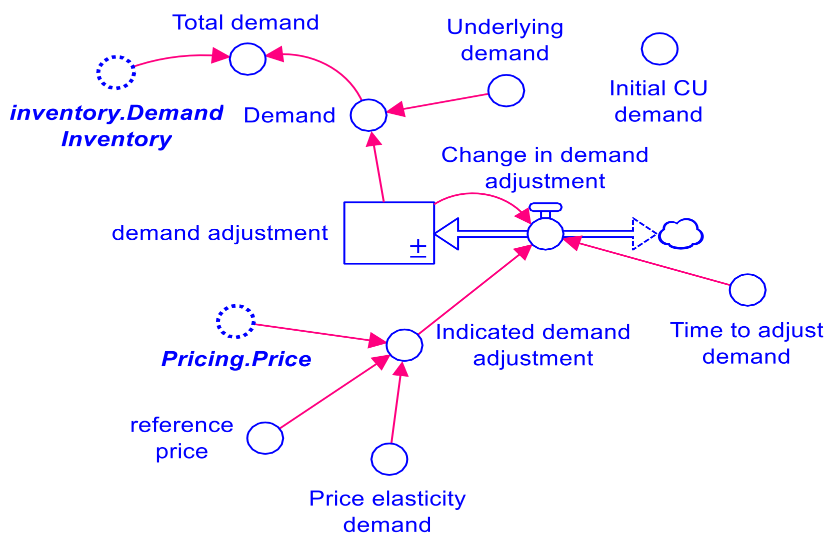

Figure 5.Stock and Flow structure of Demand Sector

Total demand is the sum of electricity demand from inventory holders and the actual demand from consumers. The actual demand is a function of the underlying demand and demand adjusment given the frequent variation in price. Demand is expressed as follows

$$Demand = Underlying\_demand * demand\_adjustment \quad (16)$$

$$Underlying\_demand = 28 + 10 * SIN\ (2 * PI * TIME / (60 * 24)) \quad (17)$$

Underlying demand is the amount of electricity demanded when price is low and fixed. With the introduction of variable pricing demand will usually respond to changes in price. Underlying demand is expressed using the SIN function to show variation in demand during peak and off peak periods. The underlying electricity demand in Ghana for the period of July 2016 is 28 MWh/minute with and amplitude of 10MWh/minute. Demand adjustment is represented as a stock that is anchored to the indicated demand adjustment over an adjustment time of 30 minutes. The indicated demand captures the variations in demand given price variation. It is simply expressed as

$$Indicated\_demand\_adjustment = (Price/reference\_price) \wedge (Price\_elasticity\_demand) \quad (18)$$

The indicated demand adjustment is determined by the price over a reference price and price elasticity of -0.37. This shows an inverse relationship between demand and price. Electricity consumers will reduce their level of consumption with an increase in price.

4.4 Modeling inventory

Inventory represent some form of storage units where electricity can be stored for later use. The idea of storing electricity is becoming inevitable with the current global goal of shifting from carbon emitting sources of energy to green energy sources in the form of solar PV and wind. These energy sources have been identified as huge potential source that have been least exploited. The challenge however is that these sources of energy are not always available and hence the need to store the power generated. For instance, power can be generated from solar units only when the sun is shining. The recent advancement in lithium ion electricity storage has paved the way for the development of larger batteries to store electricity in large quantities for domestic and industrial purposes. The owners of these storage systems could be electricity generators, consumers or third party businesses.

Inventory is modeled with the assumption that inventory holders will buy electricity when the price is low and sell when the price is high. The buy and sell price in the model is an estimation of an average price which would be subject to variation by inventory holders given the cost of holding an inventory and the market price of electricity. The figure below represents the inventory sector in the model.

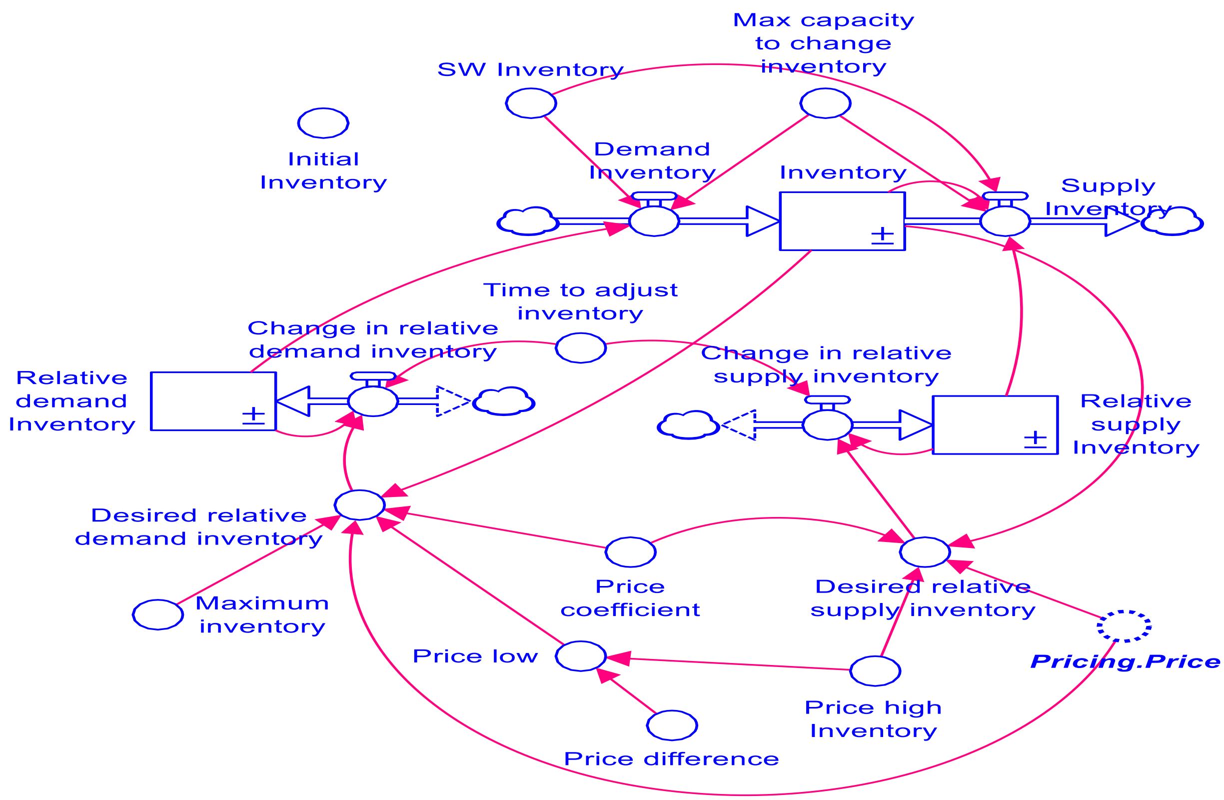

Figure 6.Stock and Flow Structure of Inventory Sector

The inventory is represented as a stock, which is increased by the demand inventory and decreased by the supply inventory. The demand inventory fills up the inventory by the amount of power purchased from generating units given the maximum storage capacity units available and the relative demand inventory. The supply inventory on the other hand depletes the inventory as it represent the amount of electricity sold from inventory which is largely determine by how much electricity is available and the relative supply inventory . The "SW inventory" variable is used to activate or deactivate the inventory sector in the model by changing the value to 1 to activate and 0 to deactivate.

The relative demand and supply inventory represent the short delays in adjusting the inventory in response to changes in price. They are anchored to the desired relative demand and supply inventory with an inventory adjustment time of 10 minutes. These are formulated with the simple rule that inventory holders will buy electricity when the price is low relative to "price low" and sell electricity if the price is high relative to "price high". This is represented in the equation below,

$$Desired\_relative\_demand\_inventory = IF\ Inventory < Maximum\_inventory\ THEN\ MIN\ (1, MAX\ (0, (Price\_low - Price)/ Price\_coefficient))\ ELSE\ 0 \quad (19)$$

$$Desired\_relative\_supply\_inventory = (IF\ Inventory > 0\ THEN\ MIN\ (1, MAX\ (0, (Price - Price\_high\_Inventory)/ Price\_coefficient))\ ELSE\ 0) \quad (20)$$

Desired relative demand inventory is formulated with the assumption that inventory holders will only buy electricity when the inventory is less than the maximum inventory. Price low is the minimum price relative to price, above which inventory holders will not buy electricity. Any price above the price low will serve as a disincentive to inventory holders. For the desired relative supply inventory, the price high is the average price below which inventory holders will not be willing to sell. The "IF THEN ELSE" is a logical function that describe the decision rule of inventory holders.

4.5 The Causal Relationship

The model consists of five main balancing feedback loops and one minor reinforcing loop. The diagram below represents the causal relationship between model variables and their polarities.

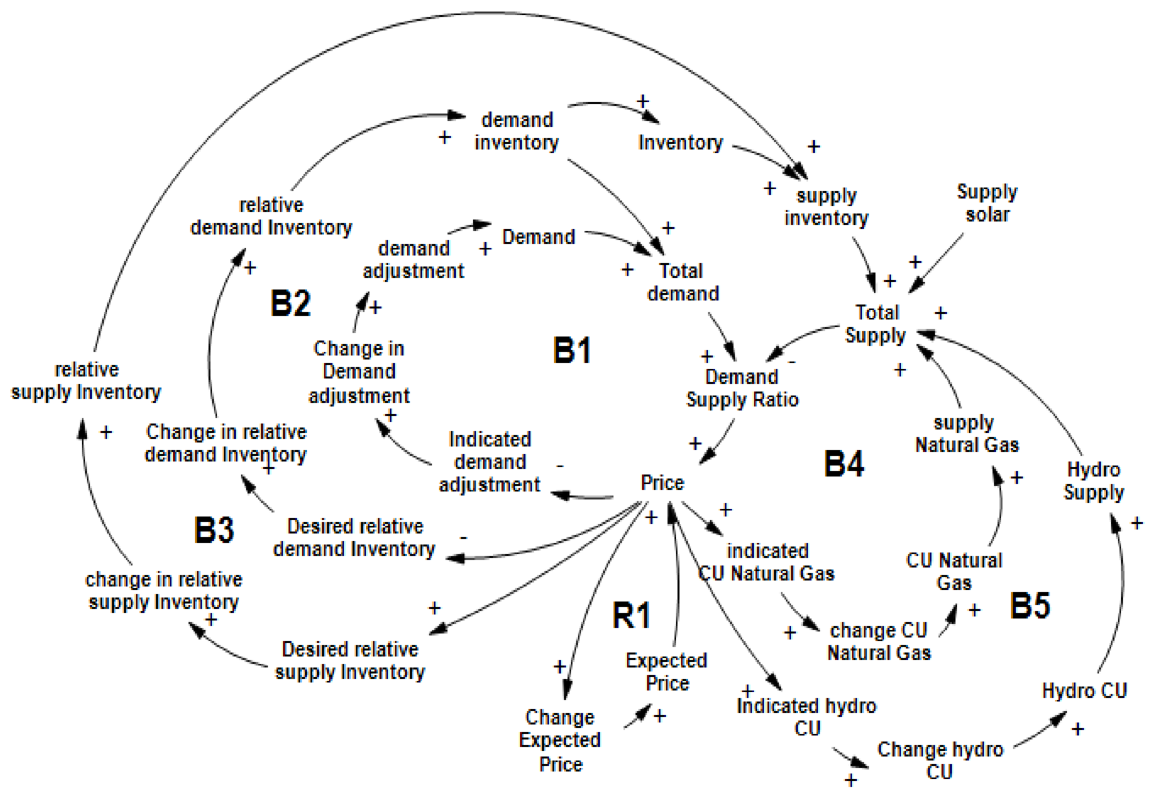

Figure 7.Detailed Causal Loop Diagram

Loop B1 and B2 are balancing feedback loops that govern the interaction between price and demand. Loop B3, B4, and B5 are also balancing feedback loops that governor the interaction between price and supply. The reinforcing feedback loop (R1) is the price adjustment loop relative to the expected market price. This loop indicates that a price increase creates the perception of a continuous increase in price in the future and a price fall creates a similar perception of a decrease in price in the future.

5. Model testing and verification

Model testing and verification is an important aspect of every system dynamics model. It is aimed at establishing confidence in the soundness and usefulness of a model (Forrester & Senge 1980). To build confidence in any system dynamics model, the model structure and behaviour are subjected to several kinds of test. These test include but not limited to dimensional consistency test, structure verification test, parameter verification test, boundary adequacy test, test of model behaviour (behaviour sensitivity) and extreme condition test.(Forrest & Senge, 1980), (Y.Barlas, 1996), (Sterman, 2000). For the purpose of this project one important test that would not be conducted is the behaviour reproduction test. This test is conducted to determine how well the model generated behaviour replicates the reference behaviour that is the behaviour of the real system. This project however does not seek to explain the underlying structure of the system under consideration that is generating the problematic behaviour but rather to test different policy scenarios over a short simulation period. Hence the most useful behaviour test for this model is the behaviour sensitivity test which is conducted with different policy choices to investigate the benefits or otherwise of those policy options. Much of the test is therefore focused on the model structure.

5.1 Dimensional consistency test

The dimensional consistency test is the most basic and first test that is conducted in any system dynamics modelling process. This test is conducted to ensure that all rate equations are correct and the units of measurement are consistent. Unit consistency gives a clear sense of direction and correctness of model equations. This test was adequately carried out with the unit and equation check tool in Stella Architect software.

5.2 Structure verification test

Structure verification test is conducted to find out whether the model structure closely represents the underlying structure of the real system. As indicated by Sterman (2000), structure verification focuses on the conformance of a model to basic physical realities. For the purpose of this project, the model structure is rather theoretical than empirical (Barlas, 1996) as most of the underlying structure and assumptions are based on economic literature rather than knowledge of the internal workings of the real system. The underlying structure of the model is presented in the previous chapter with detailed explanation of model equations and the various sectors of the model. A casual loop diagram is also used to give a detailed description of the casual relationship between the various sectors of the model. The hydro sector does not however include generation from river flow but rather is formulated as a storage system that stores electricity in the form of water during the raining season and used for generating electricity during the dry season. This assumption is made on two grounds. The first reason is due to the absence of knowledge concerning daily rate of river flow that is transformed into electricity and secondly it serves as a future policy option where hydro storage tanks can be added to the various hydro generating units.

5.3 Parameter verification test

Most of the model parameters are estimated based on current academic literature and monthly publication on the electricity sector in Ghana as well as realistic assumptions. The parameter values for the various generating sources were accessed from the monthly market data analysis for the period of April 2016. The value for the fixed price that represent the existing pricing policy is accessed from documents made available by the Public Utilities Regulatory Commission a state institution responsible for setting electricity tariffs. Data was not found for the variable "stigma" which represents the standard deviation in changes in cloud cover as such an abstract value of six was chosen to represent the variation in cloud cover. Due to the nature of this project, some other variables are used to conduct behaviour sensitivity test to see how the model response to changes in those variables. The parameter values are indicated in the table below.

Table 1.Parameter Values and Units of Measurement

Parameter	Value	Unit of Measure
Capacity Natural Gas	19	MWh/minute
Capacity solar	3	MWh/minute
Hydro Generation Capacity	18	MWh/minute
Max Capacity to change inventory	60	MWh/minute
Maximum Inventory	6000	MWh
Fixed Price	0.75	GHc/KWh
Reference Price	0.33	GHc/KWh
Price high Inventory	0.65	GHc/KWh
Price difference	0.05	GHc/KWh
Price high hydro	0.5	GHc/KWh
Price elasticity demand	-0.37	dmnl
Price Sensitivity	1	dmnl
Time of day light	360	minute

5.4 Boundary adequacy test

The boundary of the model was carefully considered with reference to the main objective and purpose of the model. As indicated in the introduction the main objective of this project is to investigate the response of demand and supply to frequent variation in price as well as the welfare effect of these variations to both suppliers and consumers. With this in mind a number of implicit assumptions were made to keep the model simple and focus on the real task of the project. The generating capacity for the individual generating sources have not been explicitly modelled to indicate the acquisition and depletion of capacity but rather represented as constants. This decision was made on two grounds. First the model is not focused on the adequacy of generation capacity and the investment decision but more on alternative pricing mechanism hence capacity is assumed to be constant whilst several sensitivity test is conducted using different pricing options and other policy choices. The second reason is the short simulation period of 7 days. Capacity acquisition and installation takes long time to complete at least 24 months which is much longer than the simulation period. Demand as represented in the model is an aggregate demand that includes domestic, commercial, and industrial demand. This level of aggregation is appropriate as it represent the total demand and growth of electricity demand for the entire country. The cost and availability of natural gas or light crude oil, which largely influence electricity supply from thermal plants, have been excluded from the model. This is because it is quite difficult to determine the frequency of change in these variables and with the short simulation period, it will be inappropriate to include these variables in the model. However, an implicit assumption was made to reflect the changes in capacity utilization for supply from thermal units with reference to changes in price. This is expressed with the nonlinear graphical function, which has been explained in the model description. Imports and exports of electricity to and from neighboring countries have not been considered in the model, as they are exogenous variables that do not affect the internal dynamics of the model. With the calculation of benefits, the fixed variable operations and maintenance cost as well as transmission and distribution charges for consumers have not been considered. These are fixed costs that are paid on monthly or annual bases and hence are not represented in the model.

6. Behavior Analysis and Policy Sensitivity

6.1 Behavior Analysis and Policy Sensitivity under Fixed Price

This section tests the model behavior by first simulating the model under the fixed pricing system. Since price is considered to be fixed, several sensitivity test is conducted with exogenous variables to investigate the response of demand and supply and in the subsequent chapter an analysis of the consumer and producer welfare with the same parameter values. The simulation is conducted under different scenarios with different variables to investigate how changes in some key variables in the electricity sector will affect demand and supply. The first scenario is based on the assumption that electricity supply is mainly from natural gas and hydro with generation capacity being 19MWh/minute and 18MWh/minute respectively. Price is fixed at 0.75GHC/KWh. One important assumption is that hydro generation is not from river flow but from a storage reservior. Price elasticity to demand is set to -0.37. The time to adjust capacity utilization for both hydro and natural gas is set to 30 minutes. The resultant behavior is represented in the graph below.

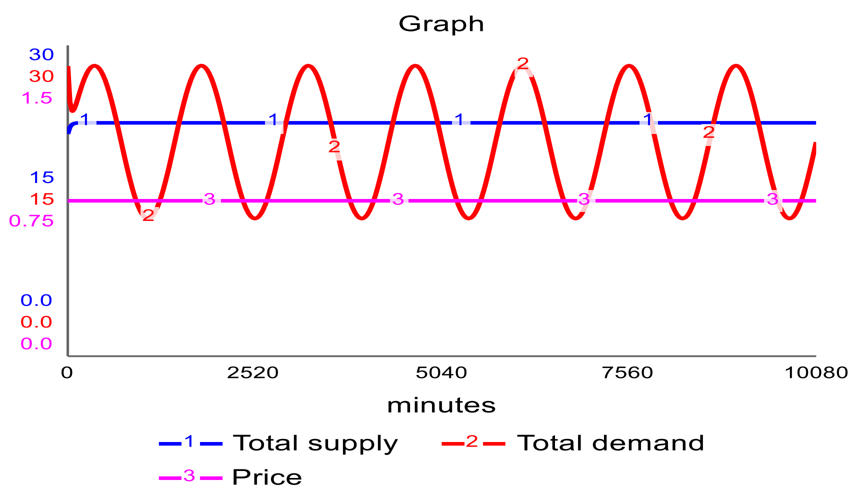

Figure 8.Total Supply, Demand, and Price

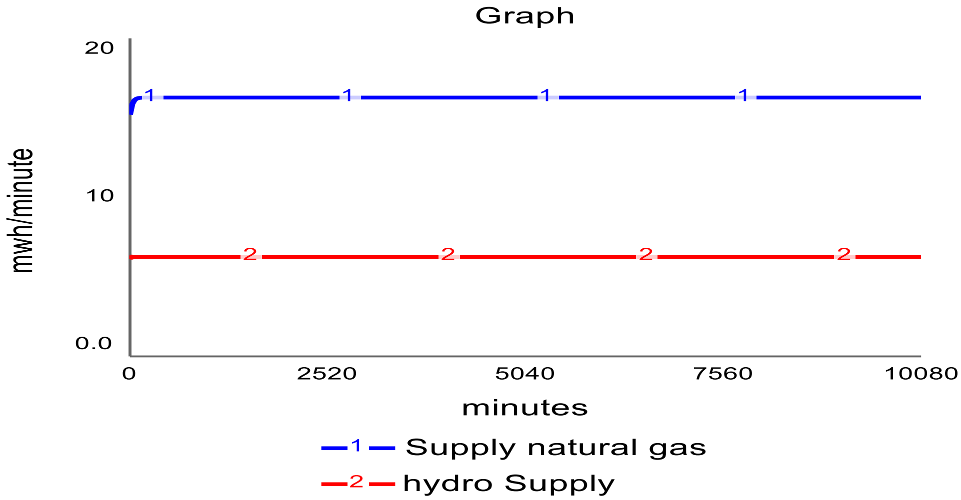

Figure 9.Supply Natural Gas and Hydro

The graphs show the simulation results for total supply and total demand as well as supply from natural gas and hydro over a 7-day period. In figure 8, total demand exhibits a cyclical behavior typical of the volatility in the electricity market that mostly experience frequent periods of high and low demand. With specific reference to Ghana, high demand is mostly experienced in the day and low demand occurring mostly after 10 pm. Total demand exceed total supply over a 24-hour cycle with peak and off peak load at 28MWh and 13MWh per minute. Supply however remains constant at 23MWh over the period since supply from natural gas and hydro are constant at 16MWh and 6.3MWh respectively due to the unchanging nature of price as indicated in figure 9. In this first scenario, we observe supply constraints during peak period that is shown in the demand supply gap as well as excess supply during off peak period where supply exceeds demand.

A second scenario is to keep price at its current value and adjust capacity for both natural gas and hydro. Natural gas capacity is adjusted to 26MWh and hydro to 24MWh. The purpose of this test is to adjust generation capacity to meet demand that happens to be the preferred option for policy designers.

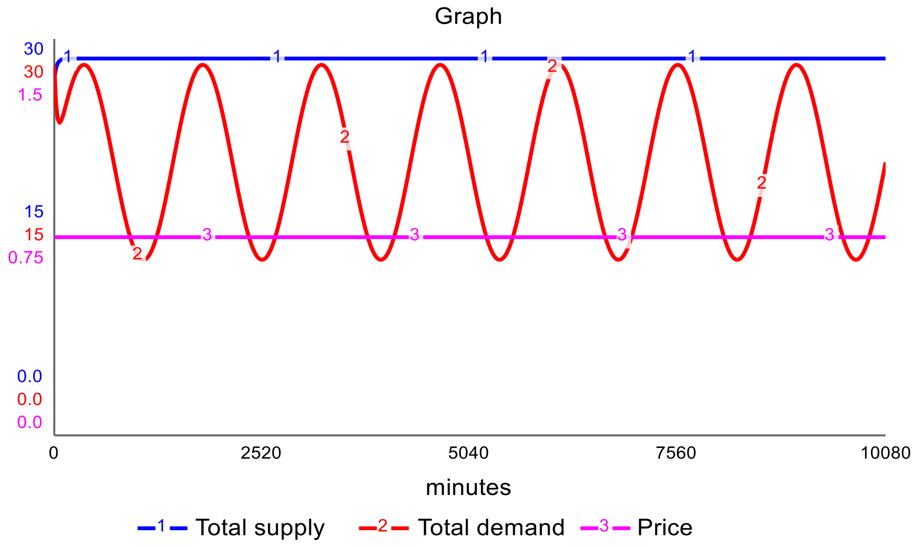

Figure 10.Total supply, demand, and price with an increase in generation capacity

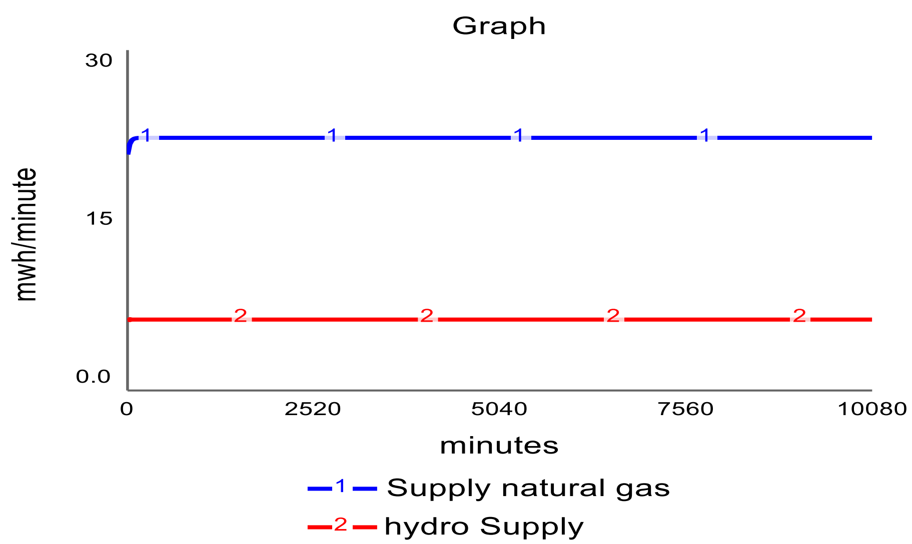

Figure 11.Supply Natural Gas and Hydro with an increase in generation Capacity

From the graph above (figure 10), with price at its initial value and an increase in generation capacity for both natural gas and hydro, we experience a constant supply of power that exceeds total demand. However, during off peak periods we observe an excess in supply more than twice the level of demand. This has cost implications for generating firms as they are maintaining capacity that is not needed over a longer period. One other important observation is that this excess supply is mainly from natural gas without any additional supply from hydro despite the increase in hydro capacity as shown in figure 11. With additional capacity, supply from natural gas increase to 22MWh/minute whereas supply from hydro remains at 6.3MWh/minute. The insight gained from this result is that electricity supply from hydro is mainly dependent on the availability of water; hence increasing hydro capacity without constant and adequate supply of water to run the turbines is not a viable option. This assumption is made with reference to the fact that low inflow of water into the hydro generation dams has been the major cause of shortfall in electricity generation from hydro plants in the early 2000 when the country experienced a period of drought.

A third policy scenario under the fixed price system is to invest in alternative sources of electricity generation in the form of solar PV. Solar PV has a high initial capital investment cost but a low operating cost. Ghana currently has a 2MW solar capacity that is insufficient to meet the current electricity needs of the country. To be able to meet the power needs of the country, there is the need to have at least 3MWh of electricity supply from solar every minute. This translates into approximately 720MW of installed solar capacity. The model response with additional supply from solar is represented in the graph below.

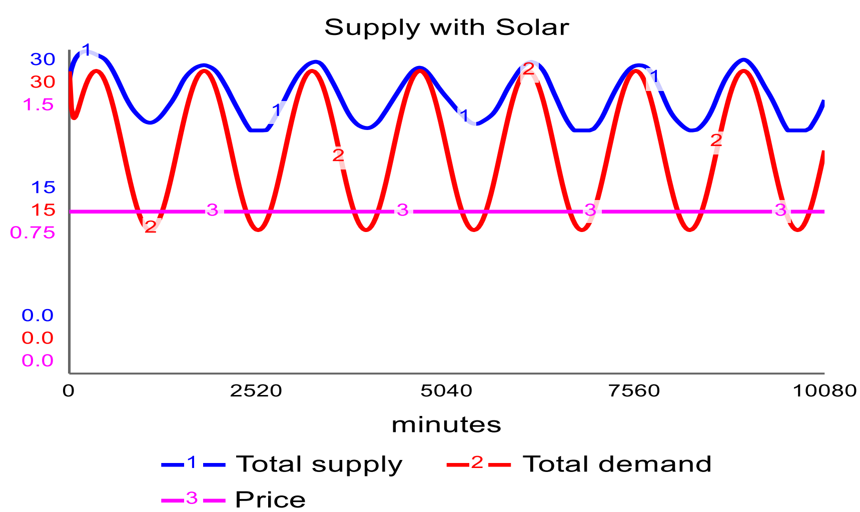

Figure 12.Total Supply, demand, and Price with additional supply from Solar

The graph indicates that total supply exceeds total demand with additional supply from solar. This closes the demand supply gap and hence eliminating the problem of blackout. We also observe excess supply during off peak periods. Since solar energy is only available during the day and absent during the night and the fact that the sun cannot be stored, battery storage can be used to store the excess power generated from solar. This can provide a reliable 24-hour power supply for both domestic and industrial use.

Following from the different scenario analysis it is evident that investing in solar capacity is the most optimal policy option with reference to capacity expansion when electricity prices are fixed for long periods.

6.2 Behavior Analysis and Policy Sensitivity under RTP

In this section, the model is used to investigate the response of demand and supply if consumers were to pay RTP instead of a fixed price. The model maintains the same parameter values for generation capacity under the fixed price system with the assumption that there is no change in capacity. Under this simulation, the switch "*SW price*" variable is changed to one to activate the RTP system. The initial simulation is done with supply from natural gas and hydro.

Figure.13 shows the simulation results for demand and supply when consumers pay real time prices.

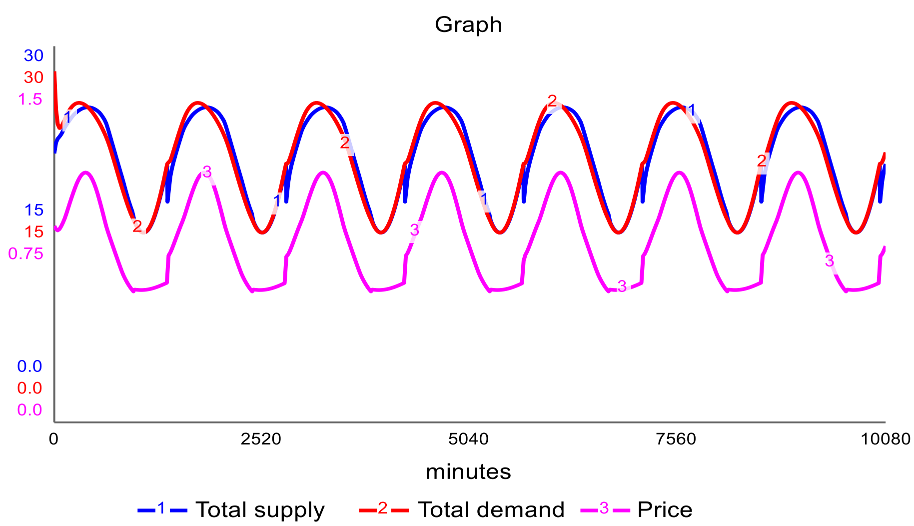

Figure 13: Total supply, demand, and Price under RTP

The simulation result shows a frequent fluctuation in electricity price in response to similar fluctuations in demand and supply. The electricity price reflects the marginal operating cost and is determined by the demand/supply conditions that exist at any given time. With the RTP system, supply increases significantly to match demand thereby eliminating the problem of blackouts. Over a 24-hour cycle, we observe a peak and off peak demand and supply of around 25MWh/minute and 15MWh/minute respectively. Price rises to 1.00 GHc/KWh during peak demand and falls to 0.53 GHc/KWh when demand surges. This resultant behavior is supported by basic economic theory that indicates that price increase with an increase in demand and falls with a fall in demand.

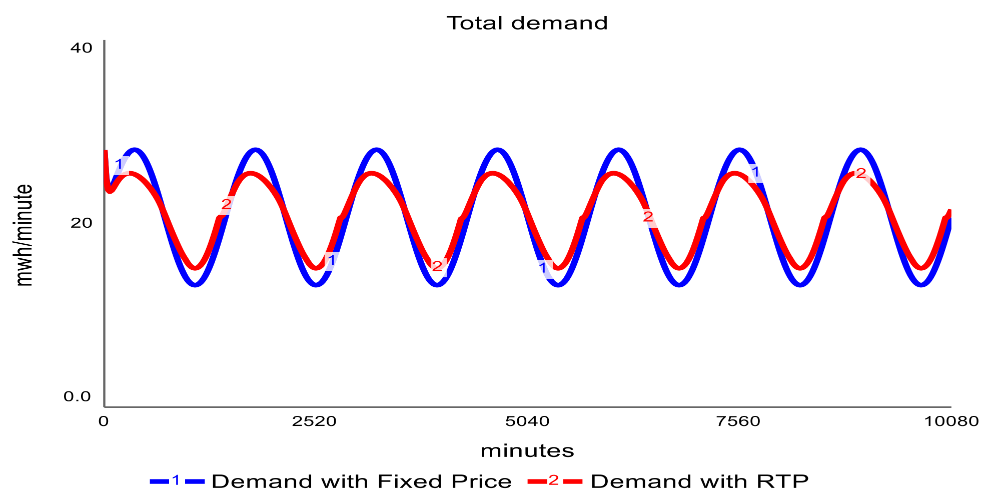

Figure 14.Comparative graph: demand under fixed price and RTP

The comparative graph shows a reduction in demand during peak periods when consumers are paying real time prices as opposed to fixed price. This is in response to price hikes during peak periods forcing consumers to conserve electricity by switching off appliances. We also observe that off-peak demand under the RTP system slightly exceeds demand under fixed price system. This means that consumers will probably try to avoid paying high prices by shifting their consumption to low price periods when the cost of generating electricity is relatively low. The RTP is important to improve electricity system efficiency and reduction in the marginal cost of suppliers in the electricity market. Under this system, the retail electricity price reflects the cost of current operating conditions.

The next scenario under the RTP is to investigate the response of price, supply and demand if investment is made in other renewable energy sources preferably solar. The model is simulated with a solar capacity of 3MWh/minute with 6 hours of sunshine every day.

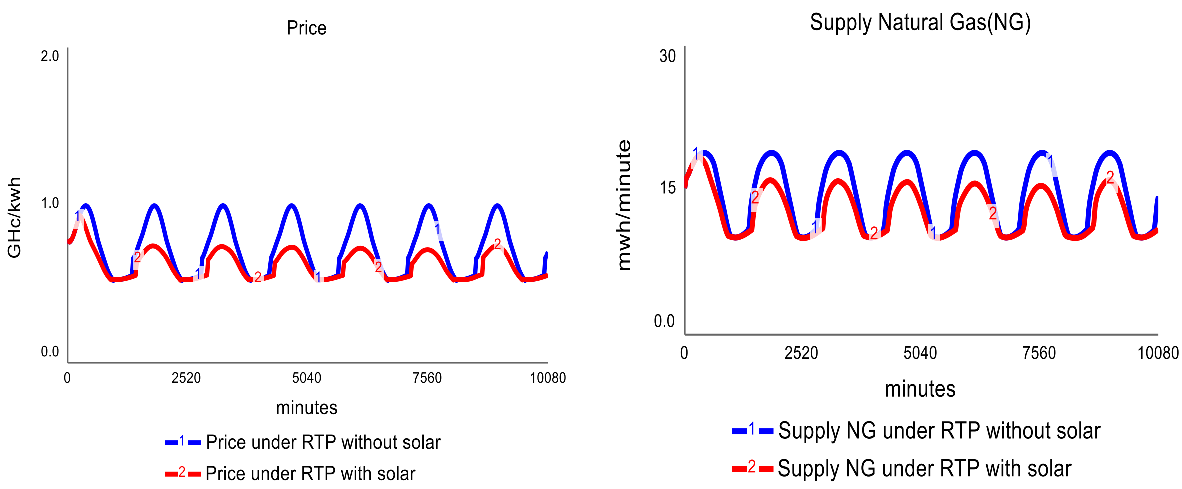

Figure 15.Comparative Graph: Price and supply from natural gas under RTP with and without solar supply

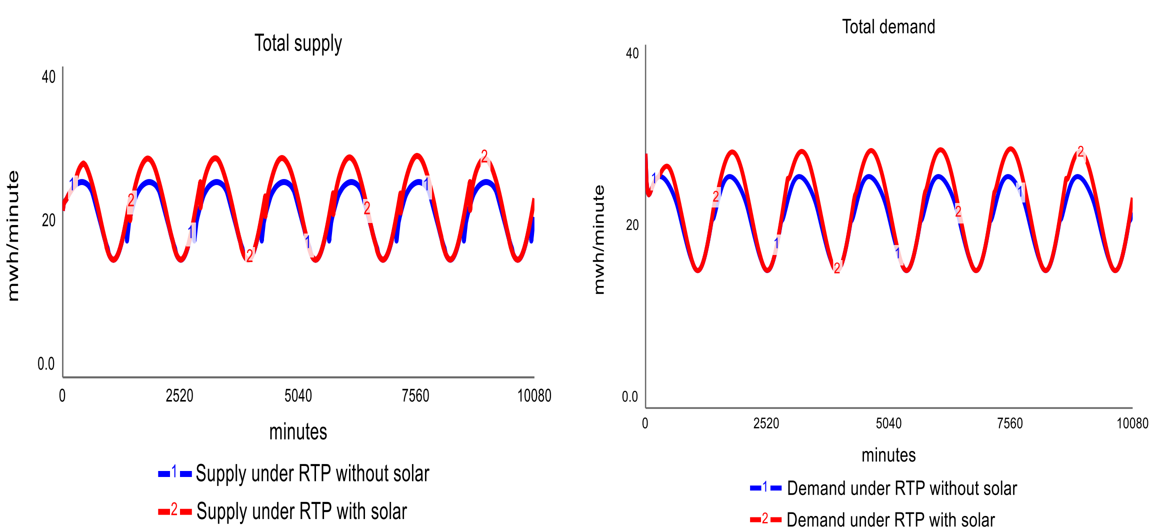

Figure 16.Comparative Graph: Total supply and demand under RTP with and without solar supply

Additional electricity supply from solar has provided significant insight about price and future investment decision in generation capacity. In figure 15, we observe a significant reduction in price during peak load periods. With solar power, price peaks at 0.72 GHc/KWh, which represent a 28% reduction in electricity price with off peak price at 0.53 GHc/KWh. This is largely attributed to the low cost of solar power production. Solar PV has no variable operating and maintenance cost since it does not require the purchase of any kind of fuel. The only cost components are the fixed operating and maintenance cost and the overnight capital cost. This makes solar power relatively cheaper compared to hydro and thermal power. We also observe a 16% reduction in supply from natural gas during peak periods from 19MWh to 16MWh. The shortfall in supply from natural gas is caused by supply from solar which drives down the price of electricity and hence a reduction in the capacity utilization of natural gas plants. This is positive for the government and operators of thermal plants as they would not need to import more gas or light crude oil and also very significant for future capacity investment decisions. With more electricity supply from solar at relatively cheaper prices, we observe a rise in demand and total supply as indicated in figure 16.

One important thing to note is that the simulation results for these variables show different results for different runs with the same parameter values. This is due to the variation in cloud cover that largely influences how much solar radiation reaches the surface. This is illustrated in the graph below.

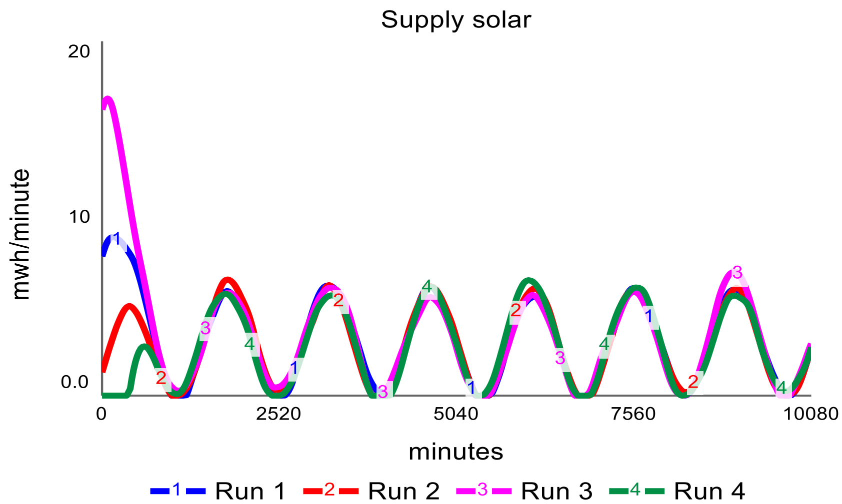

Figure 17.Comparative Runs

Figure.17 illustrates the variation in solar power due to variations in cloud cover. This shows slight variations in the other variables for each run but does not affect the general dynamics and insights gained from the model.

The final policy scenario examines the model response if storage systems were added to the electricity grid. The electricity market is a highly complex system with demand that is constantly changing and generation units that are subject to constraints during peak load periods. To avoid power cuts and electric system failure there is the need for some form of storage system. This is very relevant for electricity markets with renewable energy sources. More importantly, advancement in storage technologies, increase in fuel prices, the emergence of deregulated electricity markets and the global shift from carbon emitting energy sources to green energy has necessitated the need for storage electric systems. Since renewable energy sources have variable and intermittent output, storage systems will be an important component for future energy systems. Electricity generated from solar can therefore be stored and used when there is no solar radiation. In the model, inventory holders would buy electricity when the price is lower than 0.60GHc/KWh and sell when the price is higher than 0.65GHc/KWh. These random values are subject to change relative to the current price and market conditions. The simulation result with additional storage is tested with and without supply from solar.

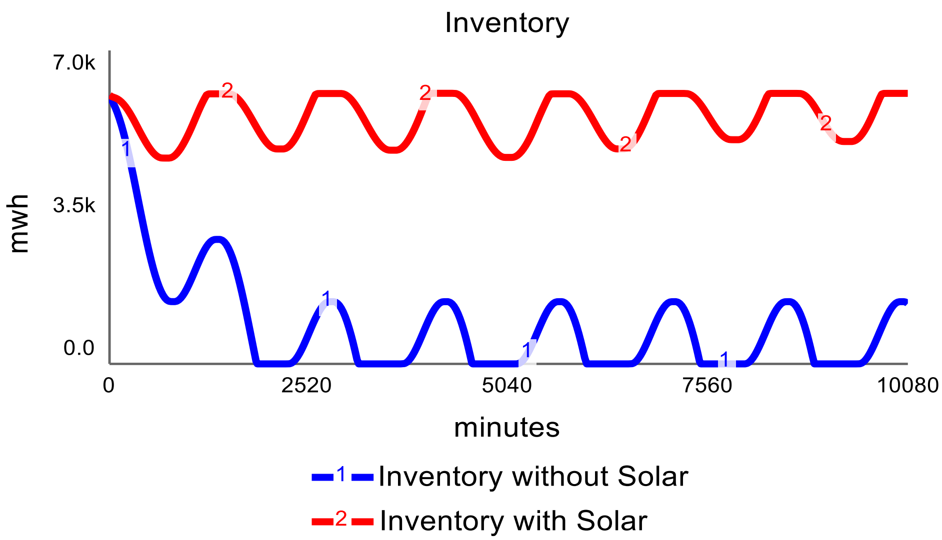

Figure 18.Comparative Graph: Inventory with and without Solar

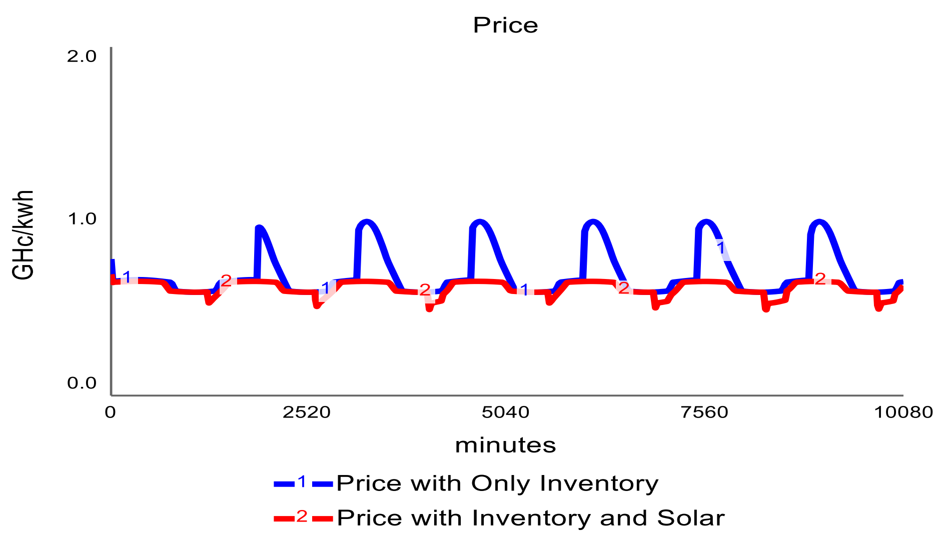

Figure 19.Comparative Graph: Price

Figure.18 shows the response of inventory when electricity is generated from less expensive renewable sources. In figures.18, we observe that without supply from solar the inventory is almost depleted because of price hikes during peak periods under RTP. However with supply from solar electricity is relatively cheaper and inventory holders can afford to hold larger inventories and only sell when prices rise a little above the price high set by the market. This creates a buffer for the electricity market. This is depicted in Figure.19 where we observe a further fall in price with extra electricity supply from storage units with peak price at 0.65GHc/KWh and off peak price at 0.49 GHc/KWh. With this fall in price, inventory holders will have to adjust their price levels to reflect the market conditions.

7. Benefits of RTP

This section examines the benefits of RTP to both consumers and producers of electricity. The benefits of RTP is estimated by calculating the peak demand reduction, reduction in capacity cost and the social welfare. The welfare benefit is a measure of the total benefits to society. It is computed as the sum of the consumer and producer surplus. The simulation results above shows the response of consumers to changes in pricing mechanism and the response of price to changes in demand/supply balances. In figure.8, we observe a peak demand of 28MWh/minute under the fixed pricing system. This peak demand however falls to 25MWh/minute represensting an 11% reduction in peak demand with the introduction of RTP. This is an indication of over consumption by consumers during peak periods since the price paid is lower than the marginal cost of producing electricity. To effectively meet the peak demand under fixed pricing, producers will have to install additional generation capacity as shown in fig.10 indicating an excess capacity during off peak periods. The RTP therefore serves as a control mechanism that ensures savings in capacity cost with a reduction in capacity investment as well as the efficient utilization of available capacity. Consumers will aviod paying higher prices during peak period by shifting consumption to off peak period when prices are relatively lower. This is reflected in fig.14 where we observe a slight increase in demand during off peak period under the RTP system relative to fixed pricing.

The welfare benefit is estimated by calculating how much consumers will be saving if they were to pay RTP instead of fixed prices and how much profit producers will make under RTP as opposed to fixed prices. This is calculated using the stock and flow diagram below and the same parameter values used for the different scenario testing.

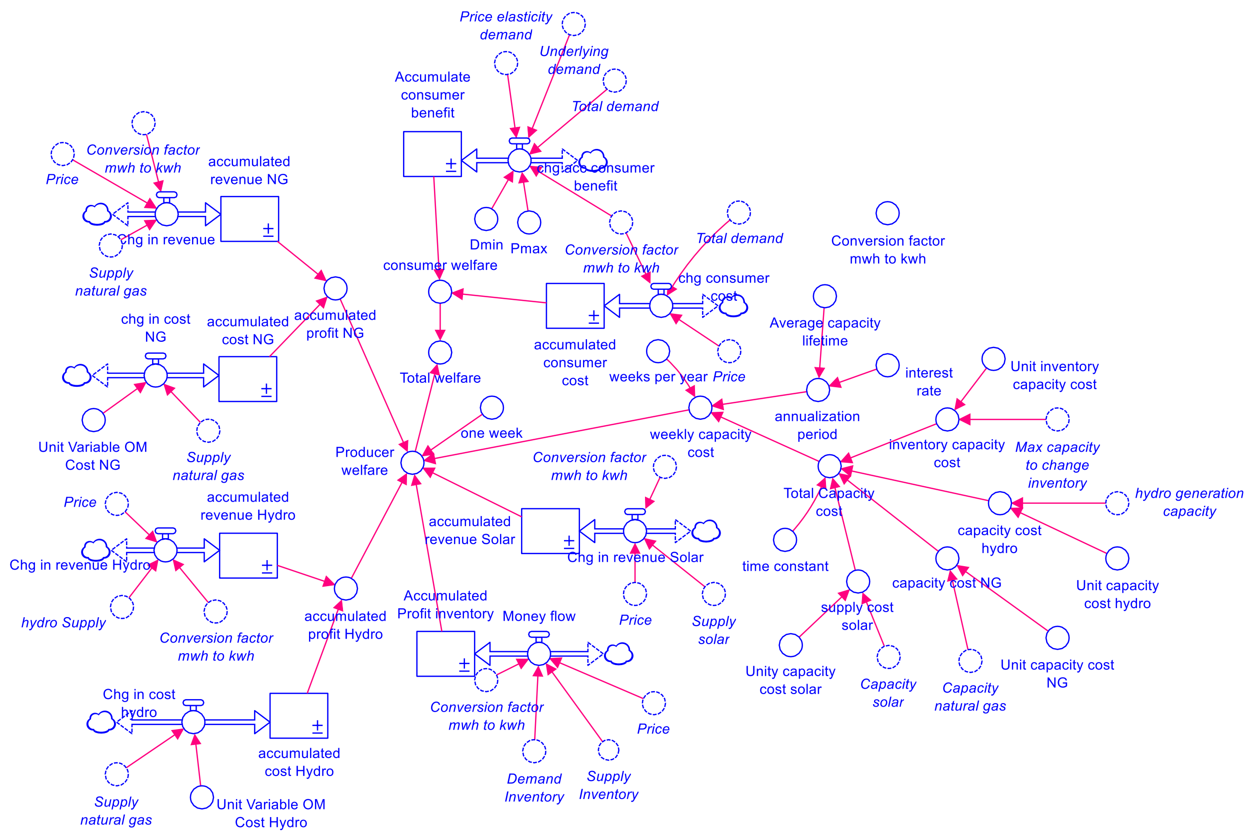

Figure 20.Stock and flow structure of Benefits

The consumer welfare is calculated as the difference between the accumulated consumer benefit and the accumulated consumer cost as represented in the equation below

$$CW = CB - ACC \tag{21}$$

Where CW is the consumer welfare, CB is the accumulated consumer benefit and ACC is the accumulated consumer cost. CB and ACC integrates the change in consumer benefits and the change in consumer cost. The change in consumer cost represent how much consumers are spending on electricity. The change in consumer benefits represent how much consumers will save.These are formulated as follows:

$$\Delta ACC = P * D \tag{22}$$

$$\Delta CB = Pmax * Dmin + Du * \frac{1}{1-1/\varepsilon}\{(\frac{D}{Du})^{1\text{-}1/\varepsilon} \text{-} (\frac{Dmin}{Du})^{1\text{-}1/\varepsilon}\} \tag{23}$$

Where ΔACC is change in consumer cost, P is price and D is demand. ΔCB is change in consumer benefits, P_{max} is the maximum price, D_{min} is the minimum demand, D_U is underlying demand and D is demand. The minimum demand and maximum price are absolute values representing the lowest demand and the highest price over the simulation period.

The producer welfare is estimated by calculting the total revenue and the variable operating and maintenance cost for each generating unit. The producer welfare therefore takes the form

$$PW = AP - CC \tag{24}$$

$$AP = AR - AC \tag{25}$$

$$AR = \int P * S \tag{26}$$

$$AC = \int C * S \tag{27}$$

Where PW is producer welfare, AP is accumulated profit, CC is Capacity cost, AR is accumulated revenue, AC is accumulated cost, P is price and S is the electricity supply from each utility. The CC is divided by 52 to get the weekly capacity cost. This is expressed in the form

$$cc = \left(\frac{capacity\ investment}{annualization\ period}\right)/52 \tag{28}$$

the capacity investment is the total cost of available capacity. The annualization period is expressed as:

$$AP = 1/\left(r + \frac{1}{lifetime}\right) \tag{29}$$

The average capacity lifetime is estimated at 25 years with an interest rate (r) of 21% per annum.

Table 2.Producer cost Components

Variable	cost (USD/MWh)
Unit Variable OM cost NG	41.2
unit Variable OM cost Hydro	5
Unit capacity cost solar	61.2
Unit capacity cost NG	12.8
Unit capacity cost Hydro	54.1
Unit Inventory capacity cost	150000

The table shows the unit variable operating and maintenance cost as well as the unit capacity cost per MWh for each utility expressed in USD terms. In the model unit of measure is converted to the local currency using the exchange rate of 4.1 GHc/USD which is sbuject to change at any given time.

8. Results

The welfare benefits for consumers and producers are represented in the table below showing how much consumers and producers will gain or loss if they switched to RTP with and without investment in cheaper renewable sources and storage systems. In previous simulation we observe different demand and supply responses with a shift in pricing systems and additional generation from renewable and supply from storage units.

Table 3.Welfare Estimates under Different Scenarios (million)GHc

	BASE CASE FIXED PRICE	RTP	RTP WITH SOLAR	RTP WITH INVENTORY	RTP WITH SOLAR AND INVENTORY
supply From NG	95	87	59	80	56
Supply from Hydro	44	42	36	41	35
Supply from Solar	0	0	21	0	22
Inventory	0	0	0	3.7	0.4
Producer Welfare	139	129	116	124	113
Consumer Welfare	5.9	10	30	13	32
Total Welfare	145	139	146	137	145

the simulation results for welfare gains provides significant insights about different pricing systems in an open electricity market. The model is simulated under different policy test scenarios. In the base case the model is simulated with a fixed price. the model is subsequently simulated with variable pricing with additional electricity supply from solar and storage units. In all test cases we observe significant changes in the total benefits for each entity. Thermal(NG) and hydro operators experience marginal fall in their profits with the introduction of variable pricing. Profits decreases from GHc95mm to GHc87mm for thermal operators and GHc44mm to GHc42mm for hydro operators with a 7% fall in producer welfare from GHc139mm to GHc129mm. Reduction in producer welfare is because of significant reduction in revenue with a marginal fall in the variable operating and maintenance cost due to reduction in peak demand. The revenue shortfall is attributed to an increase in consumption during off peak period when price is low. Consumers are however better off with an increase in savings under variable pricing from GHc5.9mm to GHc10mm. This is a results of consumers having to pay lower prices during off peak periods. Under RTP, the price of electricity is controled by market forces. Therefore to be able to meet peak demand, prices must be adjusted higher to cover the operational cost of producers. Prices are therefore automatically adjusted given the level of demand and supply. Total welfare however falls from GHC145mm under flat rates to GHC139mm under variable pricing due to a fall in producer revenue. it is however important to note that about 93% of the welfare benefits goes to producers.

The next test case investigates the welfare gains with electricity supply from solar under RTP. The results shows that consumers are much better off with additional supply from solar. Producer welfare however continues to drop from GHC129mm under variable pricing without solar to GHC119mm under variable pricing with solar with a continous drop in peak price. Consumer welfare increases significantly from GHC10mm to GHC30mm with a total welfare gain of GHC146mm. The drop in producer welfare is largely due to significant drop in supply from natural gas and hydro. With the introduction of solar, electricity prices fall drastically forcing thermal plants and hydro operators to cut down production and only generate when prices are relatively high during peak periods. For hydro producers it will be more profitable to conserve water in dams or reserviors especially during the dry season when there is less river flow. There is therefore a balance in welfare gains where consumers get a fair share of the benefits with electricity from solar coupled with variable pricing relative to RTP without supply from solar.

A comparative test case is to invest in storage units under RTP without supply from solar. Under this system inventory holders would keep very small inventories since they would be buying power at a relatively higher price and sell at an equally high price. we therefore observe a significant increase in profits for NG and hydro producers with a fall in consumer welfare as well as total welfare.

The final test case is the combination of electricity supply from solar and storage units. The storage units will store excess electricity that is generated from solar plants. With more electricity supply from solar and storage units, prices fall further with a peak price of 0.65 GHc/KWh resulting in further increase in consumer welfare. Operators of thermal and hydro plants continue to cut down supply and so does their profit margins hence a drop in producer welfare. The slow down in supply from thermal and hydro has a positive effect on production cost and a reduction in carbon emissions specifically from thermal units. There is reduction in excess capacity cost and secondly a reduction in variable operational cost in the form of fuel cost. As indicated in fig.10, for electricity supply to meet the peak load, producers will have to build additional production capacity increasing the capital cost of producers.

9. Implementation of RTP

This section examines the implementation issues related to the adoption of a smart grid with real time pricing. The project focuses on policy strategies to address the electricity shortfall in Ghana by investigating the efficiency and benefits of RTP relative to the traditional fixed pricing system. Though there is no explicit implementation structure included in the model, we examine the very relevant issues related to the implementation of a smart grid with RTP in the electricity market of Ghana in the near future. These issues revolve around new grid technologies, Project financing and societal awareness and acceptance of this policy option.The successful implementation of a smart electricity grid requires the deployment of a smart metering infrastructure also known as Advanced Metering Infrastructure(AMI) and telecommunication systems. The components of AMI include an internal meter measuring energy consumption on at least an hourly basis, an automated communication system for uploading comsumption data to a central data processing center, customer access to consumption data and notification of RTP and system emergency alerts that enable customers to respond to price signals and reduce their level of consumption during peak periods. Smart meters are designed to receive real time price signals allowing consumers to control a number of appliances in their homes and offices either manually or automatic configuration of appliances to the smart meter. A wider penetration of internet infrastructure is critical for the successful operation of smart meters. This is necessary for the constant flow and update of information across the grid transfering load data to electricity utility providers and automatic price updates at any point in time as well as customer price alerts and consumption history. Ghana currently has an internet peneration rate of about 27.8% (http://www.internetworldstats.com/stats1.htm). this means more investment needs to be made in the expansion of internet infrastructure.

The cost and financing of smart meters will be central to the implementation of RTP. The capital cost of deploying AMI include the cost of hardware and software that is meter modules, network infrastructure and network management , project management and the cost of information communication integration. A European Union(EU) energy commission report cite the average cost of installing a smart meter to be between €200 and €250. This has been collaborated by the Smart Grid Investment Grant(SGIG) program for the deployment of AMI as at 31st December 2014 with an average cost of $267 per smart meter. With about 6.4 million households in Ghana, the total capital cost of deploying AMI is estimated to be around $1.7 billion. However with advancement in technology the cost of smart meters are falling rapidly. This is cost to society and must be paid over the lifetime of the infrastructure. The immediate challenge however is the initial financing of the project. In other developing countries that are adopting a smart grid, the initial capital cost is partly borne by government and external grant as well as funding from private investors.

The final issue of great importance to the successful implementation of this policy is societal awareness and acceptance. The smart grid concept is designed to enable the active participation of consumers in the electricity system. Consumers therefore need to be actively involved in the implementation process of this policy. A starting point for consumer engagement would be public education and awareness about smart grid technologies and how it works. Consumers also need to be educated about their energy consumption and its impact on energy security. Another critical issue of concern is whether consumers would have a choice to adopt RTP or remain with fixed pricing system. This relates to legislation and regulatory amendments and the new market structure.

10. Discussion

In the wake of rapid growth in energy demand across the world, several reform projects have been undertaken by governments mostly in developing countries to address the shortfall in energy supply specifically electricity. Several policy interventions aimed at making electricity available, accessible and affordable to majority of the population were initiated. Most of these policy interventions are driven by the United Nations Sustainable Development Goals which seeks to ensure universal access to affordable, reliable and modern energy services as well as increase the share of renewable energy in the global energy mix by the year 2030 (https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals). The major challenge however for most governments has been the issue of balancing electricity supply with affordability. Social policy programmes such as tariff subsidies were introduced to relieve the poor and under priviledged from the burden of paying high energy tariffs. For the electricity sector in Ghana several reform programmes were initiated to address the inefficiencies in the electricity sector. This include but not limited to the liberalization of the electricity market by allowing private sector participation in the generation and distribution of electricity and most importantly the introduction of the automatic tariff adjustment formulae purposely to review tariffs to reflect the growing operational cost of electricity utilities. These programmes have not been effectively implemented as the electricity sector is still under full government control with consumers still paying flat rate tariffs. The tariff rate structure has been designed to achieve social and political objectives. Huge investments have been made to increase the hydro and thermal generating capacities. These generating sources have however failed to meet the growing demand of electricty due to climatic factors that affect the rainfall pattern and the instability of fuel prices that makes it somewhat difficult for thermal plants to operate at optimum capacity.

To effectively address the issue of affordability and supply of electricity, it is important to look at the electricity tariff rate design and pricing system which is an important element to improving the efficiency of electricity supply. This project shifts attention from the traditional capacity expansion programmes and focuses on alternative pricing schemes and investment in renewable sources of electricity supply. It is evident from the simulation results that the implementation of RTP in a libralized electricity market is the surest way to ensuring an efficient and uninterruptable supply of electricity. However to make electricity affordable governments need to explore cheaper alternative sources of electricity supply in the form of renewable solar energy. From the model results we observe that with RTP consumers will be better off compared to fixed pricing. Though we observe a slight decline in total welfare due to shortfalls in producer welfare, there is an appreciation in consumer welfare. The welfare distribution is however not proportional with almost 92% of welfare gains going to producers. To have a fair distribution of welfare benefits it is important to invest in relatively cheaper sources of electricity. As indicated in the results, consumers are much better off with the implementation of solar power with increases in consumption and a higher welfare gain for consumers. The abundance of solar potential in Ghana makes solar power a much cheaper source of energy compared to hydro with unpredictable rainfall pattern and thermal plants whose operations are mostly impeded by the non avialability of natural gas and volatility in world market oil prices. Much of the concerns raised for less investment in solar PV is the high initial capital cost. However recent report published by bloomberg indicates a rapid decline in the cost of solar PV with projections indicating that solar power could become the cheapest form of electricity.

With recent advancement in storage technologies and a decline in battary cost, it is becoming relatively cheaper to store electricity in large quantities for domestic and commercial use. These storage systems will compensate for the volatility in electricity from renewable sources. However for these policy options to be successful electricity pricing should be determined by market forces under a deregulated electricity market.

11. Conclusion

This project investigates the role of dynamic pricing in a smart electricity market and its effect on demand and supply and welfare of producers and consumers. A system dynamics methodology is used to gain a qualitative insight of the inter play between demand, supply and price. Different policy scenarios were tested to identify an optimal policy option for the future electricity market of Ghana. It is evident from the model structure and simulation results that to effectively solve the shortfall in electricity supply there is the need to address the issue of electricity tariff design. RTP as experimented in this study has proven to be a better pricing alternative relative to the traditional flat rate system. The study found that RTP can be an effective mechanism to meet peak loads as prices are adjusted in real time to cover the cost of electricity supply. It also provides substantial benefits to electricity producers by reducing the variable operation and maintenance cost as well as capital investment cost with significant benefits to consumers reflected in increases in consumer welfare. The study however observed that to maximize the benefits to consumers there is the need to shift from cost intensive sources of electricity supply such as gas powered thermal plants to cheaper renewable sources of electricity with storage units that would serve as backup systems. The implementation of RTP is a critical area that has been briefly examined. Without an explicit stock and flow implementation structure, the project briefly discussed the technology requirement and cost components for implementing RTP. Other issues discussed include consumer involvement in the implementation process. The model-generated values for welfare may not reflect the actual reality, however, the most important lesson that is elicited from the results shows that with real time pricing and investment in renewal energy sources and storage units, supply of electricity will be most efficient and both consumers and producers will be much better off.

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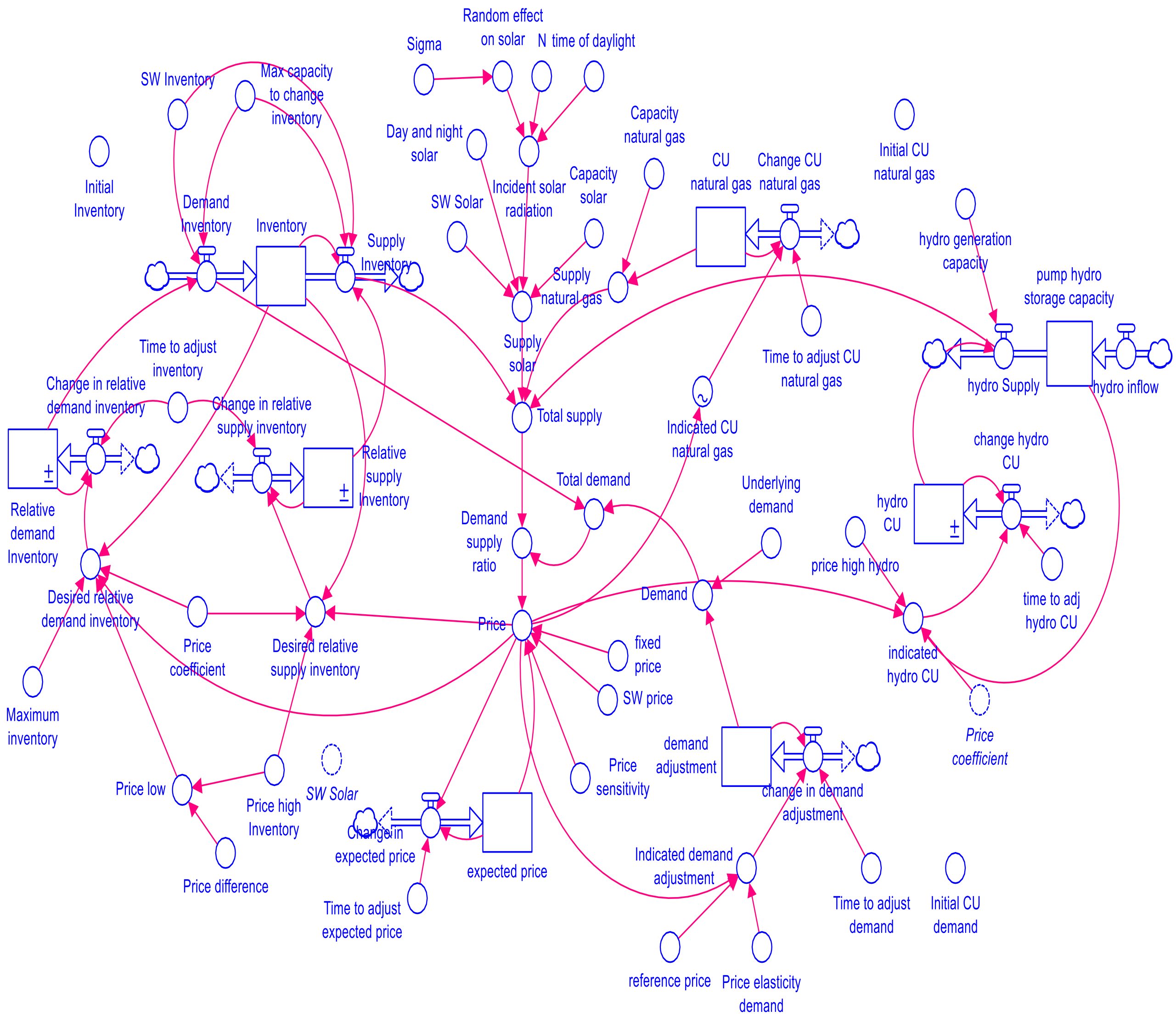
Appendices

Complete Stock and Flow Structure

Figure 21.Complete Model Overview



Model Equations

Top-Level Model:

Accumulate_consumer_benefit(t) = Accumulate_consumer_benefit(t - dt) + (chg_acc_consumer_benefit) * dt
INIT Accumulate_consumer_benefit = 0
INFLOWS:
chg_acc_consumer_benefit =
Pmax*Conversion_factor_mwh_to_kwh*(Dmin+Underlying_demand*(1/(1-1/Price_elasticity_demand))*((Supply_with_blackouts/Underlying_demand)^1-1/Price_elasticity_demand-(Dmin/Underlying_demand^1-1/Price_elasticity_demand)))

accumulated_consumer_cost(t) = accumulated_consumer_cost(t - dt) + (chg_consumer_cost) * dt
INIT accumulated_consumer_cost = 0
INFLOWS:
chg_consumer_cost = (Price*Supply_with_blackouts)*Conversion_factor_mwh_to_kwh

accumulated_cost_Hydro(t) = accumulated_cost_Hydro(t - dt) + (Chg_in_cost_hydro) * dt
INIT accumulated_cost_Hydro = 0
INFLOWS:
Chg_in_cost_hydro = Supply_natural_gas*Unit_Variable_OM_Cost_Hydro

accumulated_cost_NG(t) = accumulated_cost_NG(t - dt) + (chg_in_cost_NG) * dt
INIT accumulated_cost_NG = 0
INFLOWS:
chg_in_cost_NG = Supply_natural_gas*Unit_Variable_OM_Cost_NG

Accumulated_Profit_inventory(t) = Accumulated_Profit_inventory(t - dt) + (Money_flow) * dt
INIT Accumulated_Profit_inventory = 0
INFLOWS:
Money_flow = ((Supply_Inventory-Demand_Inventory)*Conversion_factor_mwh_to_kwh)*Price

accumulated_revenue_Hydro(t) = accumulated_revenue_Hydro(t - dt) + (Chg_in_revenue_Hydro) * dt
INIT accumulated_revenue_Hydro = 0
INFLOWS:
Chg_in_revenue_Hydro = Price*(hydro_Supply*Conversion_factor_mwh_to_kwh)

accumulated_revenue_NG(t) = accumulated_revenue_NG(t - dt) + (Chg_in_revenue) * dt
INIT accumulated_revenue_NG = 0
INFLOWS:
Chg_in_revenue = Price*(Supply_natural_gas*Conversion_factor_mwh_to_kwh)

accumulated_revenue_Solar(t) = accumulated_revenue_Solar(t - dt) + (Chg_in_revenue_Solar) * dt
INIT accumulated_revenue_Solar = 0
INFLOWS:
Chg_in_revenue_Solar = Price*(Supply_solar*Conversion_factor_mwh_to_kwh)

CU_natural_gas(t) = CU_natural_gas(t - dt) + (Change_CU_natural_gas) * dt
INIT CU_natural_gas = Initial_CU_natural_gas
INFLOWS:
Change_CU_natural_gas = (Indicated_CU_natural_gas-CU_natural_gas)/Time_to_adjust_CU_natural_gas

demand_adjustment(t) = demand_adjustment(t - dt) + (change_in_demand_adjustment) * dt
INIT demand_adjustment = Initial_CU_demand
INFLOWS:
change_in_demand_adjustment = (Indicated_demand_adjustment-demand_adjustment)/Time_to_adjust_demand

expected_price(t) = expected_price(t - dt) + (Change_in_expected_price) * dt
INIT expected_price = 0.6
INFLOWS:
Change_in_expected_price = (Price-expected_price)/Time_to_adjust_expected_price

hydro_CU(t) = hydro_CU(t - dt) + (change_hydro_CU) * dt
INIT hydro_CU = 0.7
INFLOWS:
change_hydro_CU = (indicated_hydro_CU-hydro_CU)/time_to_adj_hydro_CU
Inventory(t) = Inventory(t - dt) + (Demand_Inventory - Supply_Inventory) * dt
INIT Inventory = Initial_Inventory
INFLOWS:
Demand_Inventory = SW_Inventory*Relative_demand_Inventory*Max_capacity_to_change_inventory
OUTFLOWS:
Supply_Inventory = SW_Inventory*(IF Inventory<0.001 THEN 0 ELSE Relative_supply_Inventory*Max_capacity_to_change_inventory)
pump_hydro_storage_capacity(t) = pump_hydro_storage_capacity(t - dt) + (hydro_inflow - hydro_Supply) * dt
INIT pump_hydro_storage_capacity = 0
INFLOWS:
hydro_inflow = 9000/1440
OUTFLOWS:
hydro_Supply = hydro_generation_capacity*hydro_CU
Relative_demand_Inventory(t) = Relative_demand_Inventory(t - dt) + (Change_in_relative_demand_inventory) * dt
INIT Relative_demand_Inventory = 0
INFLOWS:
Change_in_relative_demand_inventory = (Desired_relative_demand_inventory-Relative_demand_Inventory)/Time_to_adjust_inventory
Relative_supply_Inventory(t) = Relative_supply_Inventory(t - dt) + (Change_in_relative_supply_inventory) * dt
INIT Relative_supply_Inventory = 0
INFLOWS:
Change_in_relative_supply_inventory = (Desired_relative_supply_inventory-Relative_supply_Inventory)/Time_to_adjust_inventory
accumulated_profit_Hydro = accumulated_revenue_Hydro-accumulated_cost_Hydro
accumulated_profit_NG = accumulated_revenue_NG-accumulated_cost_NG
annualization_period = 1/(interest_rate+(1/Average_capacity_lifetime))
Average_capacity_lifetime = 25
capacity_cost_hydro = (hydro_generation_capacity*Unit_capacity_cost_hydro)
capacity_cost_NG = (Capacity_natural_gas*Unit_capacity_cost_NG)
Capacity_natural_gas = 19
Capacity_solar = 3
consumer_welfare = Accumulate_consumer_benefit-accumulated_consumer_cost
Conversion_factor_mwh_to_kwh = 1000
Day_and_night_solar = SIN(2*PI*TIME/(60*24))
Demand = Underlying_demand*demand_adjustment
Demand_supply_ratio = Total_demand/Total_supply
Desired_relative_demand_inventory = IF Inventory<Maximum_inventory THEN MIN(1, MAX(0, (Price_low-Price)/Price_coefficient)) ELSE 0
Desired_relative_supply_inventory = (IF Inventory>0 THEN MIN(1, MAX(0, (Price-Price_high_Inventory)/Price_coefficient)) ELSE 0)
Dmin = 15
fixed_price = 0.75
hydro_generation_capacity = 18

Incident_solar_radiation = SMTHN(Random_effect_on_solar, time_of_daylight, N)
Indicated_CU_natural_gas = GRAPH(Price)
(0.000, 0.000), (0.100, 0.000), (0.200, 0.020), (0.300, 0.080), (0.400, 0.278), (0.500, 0.478), (0.600, 0.666), (0.700, 0.793), (0.800, 0.920), (0.900, 0.967), (1.000, 0.996)
Indicated_demand_adjustment = (Price/reference_price)^(Price_elasticity_demand)
indicated_hydro_CU = (IF pump_hydro_storage_capacity>0 THEN MIN(0.95, MAX(0, (Price-price_high_hydro)/Price_coefficient))ELSE 0)
Initial_CU_demand = 1
Initial_CU_natural_gas = 0.8
Initial_Inventory = 6000
interest_rate = 0.23
inventory_capacity_cost = (Max_capacity_to_change_inventory*Unit_inventory_capacity_cost)
Max_capacity_to_change_inventory = 60
Maximum_inventory = 6000
N = 3
one_week = 1
Pmax = 1
Price = expected_price*(1+Price_sensitivity*(Demand_supply_ratio-1))*SW_price+(1-SW_price)*fixed_price
Price_coefficient = 0.1
Price_difference = 0.05
Price_elasticity_demand = -0.37
price_high_hydro = 0.5
Price_high_Inventory = 0.65
Price_low = Price_high_Inventory-Price_difference
Price_sensitivity = 1
Producer_welfare = (accumulated_profit_Hydro+accumulated_profit_NG+accumulated_revenue_Solar+Accumulated_Profit_inventory)-weekly_capacity_cost*one_week
Random_effect_on_solar = NORMAL(1, Sigma)
reference_price = 0.33
Sigma = 3
supply_cost_solar = (Capacity_solar*Unity_capacity_cost_solar)
Supply_natural_gas = (Capacity_natural_gas*CU_natural_gas)
Supply_solar = SW_Solar*Capacity_solar*MAX(0, Day_and_night_solar+Incident_solar_radiation)
SW_Inventory = 0
SW_price = 0
SW_Solar = 0
time_constant = 1
time_of_daylight = 360
time_to_adj_hydro_CU = 30
Time_to_adjust_CU_natural_gas = 30
Time_to_adjust_demand = 30
Time_to_adjust_expected_price = 30
Time_to_adjust_inventory = 10
Total_Capacity_cost = (supply_cost_solar+capacity_cost_NG+capacity_cost_hydro+inventory_capacity_cost)*time_constant
Total_demand = Demand+Demand_Inventory
Total_supply = Supply_natural_gas+Supply_solar+Supply_Inventory+hydro_Supply
Total_welfare = Producer_welfare+consumer_welfare
Underlying_demand = 28+10*SIN(2*PI*TIME/(60*24))

Unit_capacity_cost_hydro = 54.1*4.1
Unit_capacity_cost_NG = 12.8*4.1
Unit_inventory_capacity_cost = 150000*4.1
Unit_Variable_OM_Cost_Hydro = 5*4.1
Unit_Variable_OM_Cost_NG = 41.2*4.1
Unity_capacity_cost_solar = 61.2*4.1
weekly_capacity_cost = (Total_Capacity_cost/annualization_period)/weeks_per_year
weeks_per_year = 52
{ The model has 104 (104) variables (array expansion in parens).
In 1 Modules with 0 Sectors.
Stocks: 16 (16) Flows: 18 (18) Converters: 70 (70)
Constants: 42 (42) Equations: 46 (46) Graphicals: 1 (1)
}