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THE DESIGN OF ELECTRICITY MARKETS IN DEVELOPING ECONOMIES: A DIFFERENTIAL GAMES AND OPTIMAL CONTROL METHODS APPLICATION

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Abstract

The design of an efficient electricity market for developing countries is a challenging task. The policy makers in these markets face challenges of poor investor interest, low consumer access, poor government structures, etc. There is also a need to meet global trends in reducing greenhouse emissions while improving electricity access and meeting social goals. These objectives can be conflicting especially in the early stages of development of green technologies for electricity generation. This dissertation is divided into four main sections; (1) the design of a privatized market structure with a serious entrant firm, (2) Optimal Taxing Strategy to Increase Competitiveness of Green Utility Supplier, and (3) Measuring the effects of competition and privatization in electricity Markets.

The first study focuses on electricity markets in developing economies. Electricity utilities in developing economies face the challenge of increasing their network size while facing regulatory instruments like emission taxes in an underdeveloped network. The main challenge is the appropriate pricing strategy to implement to maximize long run profits for the incumbent. While for the entrant, there is a need to maximize long run profits and stay in the market. In addition, developing economies often have a monopolistic electricity market and low levels of electricity access. To address these challenges, this work identifies the pricing strategy for the utility players in a newly established competitive market. The pricing and network dynamics of a rational profit maximization entrant utility competing with a profit maximizing dominant incumbent is investigated. Each utility seeks to identify a pricing path that maximizes its long run profits. The analysis presented consist of nine distinct cases. Using optimal control theory, the problem is modeled as a dynamic differential game; in this case, a Nash differential game under the assumption that the market players simultaneously make pricing decisions. The variable of choice is the price while the network size is the outcome. The explicit equilibrium solution is obtained by solving a set of two second order differential equations for the Nash equilibrium. Both utilities adopt an increasing pricing path and the steady state network size depends on the price levels set by the competitor and the model parameters. The policy implication of these equilibrium solutions is also presented.

The second study focuses on implementing a taxing strategy on the fossil fuel generator incumbent to improve the competitiveness of renewable energy utilities. The effects of climate change are starting to have an economic impact on developing economies. The heavy use of fossil fuels and the high investments costs required to utilize renewable energy sources in electricity generation exacerbates this problem by limiting entry of renewable energy sources. Unlike subsidies, implementing an optimal taxing policy on conventional energy sources can mitigate the competitive disadvantage of renewable source in terms without placing a steeper financial burden on the government. The main objective of this project is to determine an optimal taxing strategy that minimizes social costs due conventional energy sources and the optimal pricing strategies implemented by competing firms where the incumbent firm uses conventional energy sources and the entrant firm introduces renewable energy sources. The demands rates for both services does not only depend on the price levels but also on the consumers awareness of the environmental impacts due to conventional energy sources. This project shows that implementing an optimal taxing strategy raises the prices of fossil fuel energy therefore minimizing the pricing disadvantage that renewable energy utilities face. Using a three player Stackelberg differential game model where the policy maker is the leader and two competing utilities are the followers, an optimal pricing path and taxing policy are derived for the utility firms and the policy maker respectively. The final study focuses on quantitatively measuring the effects of introducing privatization and competition in electricity markets. The effects are measured through three performance measures which are price, urban access to electricity, rural access to electricity, and system losses. The data for this analysis comes from 15 Sub-Saharan African, 16 Latin American and Caribbean, 13 European, and 6 Middle East and North African countries for a period ranging from 1990 to 2015. Using fixed effects model, the results show that privatization has a positive correlation with access to electricity, while lack of competition has a negative correlation with access to electricity. This analysis also provides insights on policy changes that can be implemented to improve the performance of electric utilities. An emphasis on Sub-Saharan Africa and Latin America is made throughout the analysis as these regions are the least developed amongst the regions in this study and they show poor performance of utilities as measured by the three metrics used in this analysis.

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Chapter 1

Introduction

1.1 Background

1.1.1 Regulated Electricity Markets

Regulated markets generally have a single utility provider that has monopoly power over the entire electricity supply chain i.e generation,trading, transmission, distribution, and retail. Historically, all electricity markets were regulated markets. However this has since changed as the majority of electricity markets today are deregulated markets. Even under competitive markets, there still exists some form of regulation. Regulation is implemented as a means to: (1) to set a reasonable rate of return for the investors and (2) to attract investment in order to satisfy consumer demand. The regulatory authority can be the government, local municipality, or a private board. In electricity markets, there exist several ways to achieve the goals set by the regulator. These methods include (1) Rate-of-Return(ROR) and (2) Perfomance-Based Ratemaking(PBR).

Under ROR method, the regulator must conduct thorough research in order to determine the following; (1) Costs incurred by the utility supplier, (2) Value of investment, and (3) Appropriate rate of return on the invested capital. The process of gathering enough information to determine the steps above can be cost intensive to the regulator. The PBR method introduces a mechanism that attempts to reduce this cost of information gathering [1]. [1] identifies the following as the main policy variables that can be implemented to achieve the goals of electricity regulation:

- Regulated Tariffs- The regulator gives the utility the total revenue it should get from serving its current customers. The utility provider can determine the price it can set to achieve this revenue. In an ideal setting, this price will be set at the marginal cost of providing electricity to each customer.
- Allowed investment- The regulator sets the allowable levels of capital in each of the

stages of the electricity chain; generation, transmission, and distribution.

- Access rules- This is a policy instrument that involves the entry and exit of the market players.
- Quality of service requirement- It is difficult to measure quality in many markets, however , Rothwell and Gomez [1] generally describes the following as the measures of quality in electricity markets ; (1) reliability, (2) power outages and voltage disturbances, and (3) consumer satisfaction.

Regulatory Process

The goal of the regulator is to create a regulatory process that maintains an arrangement between the regulator and the market players that maximizes social welfare by reducing social costs incurred by the public and maximizing social benefits from the participation of the market players in the market. There is evidence that supports that in some cases government ownership with government oversight maximizes welfare. This condition is satisfied when the government operates in an efficient way. Most governments in the developing world lack the effective regulatory frameworks. This might be due to high levels of corruption or political instability. Under such conditions and the uncertainty of regulatory directives, the return value to the investor can be substantially diminished [81]. Therefore, the likelihood of government ownership with government oversight maximizing social welfare in developing countries is minimal. However, there is strong evidence that supports that private ownership with independent regulation is more equipped to minimize social cost of electricity provision thus maximizing social welfare better than the government ownership with government regulation framework. The former is more feasible in the deregulated markets, and therefore the developing markets can achieve these levels of efficiency by deregulating their electricity markets. Rothwell and Gomez [1] establish that it is important to ensure independence between branches of government and the regulator as this minimizes the political influence on the prices set by the utilities. It is also important to maintain independence between the regulator and the the utility to reduce the chances of regulations that maximize utility profits at the expense of the consumers. In fact, insurance of independence is so important that some countries have conflict of interests legislation to ensure the highest level of independence is attained [1]. This regulatory framework can be implemented in the electricity markets in the form of ROR and the PBR.

Rate of Return Regulation

The rate of return regulation involves determining the allowed costs and investments by the utility and then setting up an allowed level of return such that the utility appropriate earnings on its investment. Rothwell and Gomez [1] summarizes this process in three points;

1. The utility or the regulator argues that the tariff is too low/high because the cost allowance or allowed rate of return is too low/high.

2. Both parties negotiate a new set of expenses allowed and the new rate of return.

3. Tariffs are adjusted to meet the new rate of return allowed by the regulator.

The rate of return has its advantages especially in terms of investor confidence in having a fair opportunity to receive appropriate profits for investments. However, it is only sustainable in a non competitive market. It also provides little to no incentive to the utility to operate efficiently. In times of high inflation, the rate evaluation has to occur frequently and this proves to be costly in the long run. The rate of return regulations provides a means for companies to shift costs from competitive markets to non-competitive markets [29].

Perfomance Based RateMaking

The perfomance based ratemaking works as follows. The regulator uses the utility's observed and projected costs to set up the initial price. This price is the baseline for the utilities for a set period of time. This time period is usually set as a 12 month period. Also, the regulator sets incentives for the utility to reduce costs , improve efficiency or increase benefits to the consumers. Perfomance metrics are put in place in order to discourage utilities from creating savings by cutting on safety, reliability and quality. A framework to share the resultant savings is established between the regulator and the utilities. The provision of the incentives is the main difference between ROR nad PBR .The performance based ratemaking is designed on the basis of information asymmetry between the regulated utilities and regulators. It emphasizes ratemaking methods that will lead to performance without excessive regulatory oversight. Historically, it has been used as a means to decouple the link between the utility's revenue and the volume of its sales. This is achieved through an automatic mechanism that adjusts rates based on the over-or-under recovery of the target revenues [29]. Some of the main objectives of PBR include , reduced costs for the utility, improved quality of service, appropriate allocation of rewards and risk between the utility and the consumers. The main advantages of PBR can be summarized as follows:

1. Improved resource efficiency,

2. Reduced administrative and regulatory costs,

3. Improved allocative efficiency,

4. Easier introduction of new services, and

5. Compatibility with transition to competition.

While there are a number of benefits of the PBR methods. there are a number of drawbacks from using this regulating method. The main disadvantages of PBR are as follows:

1. Reduced quality of service,
2. Questionable efficiency benefits,
3. Questionable administrative costs savings,
4. Limited ability to incorporate environmental and social goals, and
5. Undesirable equity impacts.

While the PBR method gives incentive to utility companies to reduce costs and increase benefits to the consumers which can be similar to a competitive market, it is only a transition to competitive markets. This mechanism also requires the regulator to carefully design the incentive structure, performance metrics in order to induce the desired benefits. The performance metrics set needs to be measurable in order for the regulator to evaluate each utility. This can prove to be difficult for the regulator. It is also difficult to generalize the PBR methods in the presence of multiple players and different technologies.

The ROR and PBR work best in regulating a monopoly utility. These methods are not effective in the case competitive markets. It is still important for the regulator to develop a strategy that can be used to monitor the welfare of consumers in a competitive market.

1.1.2 Public Choice Theory of Regulation

The theory of public interest of regulation carries the assumption that regulation serves the interests of the consumers. In this case it is the assumptions that the government or the private regulatory authority serves the interest of the consumers by implementing policies the improve consumer welfare, protects the environment by inducing a restriction on the actions by the firms that can reduce consumer welfare or damage the environment. This assumption is challenged by the public choice theory of regulation. The public choice of regulation claims that all individuals are driven by self interest [3] i.e all decision making individuals be it public servants or independent individuals. It is also a theory that put forwards that governments can also fail.

The premise of the public theory of regulation suggests that not all regulatory processes have the objective of maximizing social welfare. It suggests that regulatory agencies through its workers cannot be exempted from the rational axioms that a decision maker will alway behave as if he or she is maximizing an individual utility. This notion of self interest at the expense of public interest is exacerbated in developing countries where the levels of corruption are high. The majority of developing countries have a corruption perception index (CPI) < 40 [5]. The averages of the worst performing regions are as follows; Sub-Saharan Africa (32), East Europe and Central Asia (34). Corruption is not limited to the least developed regions, however its impact on growth is greater in developing countries.

Public choice theory implies that the regulatory process is one in which different players seek to maximize their on benefits. The firms can use the regulatory process to maintain a monopolistic market structure, while consumers will use the regulatory process as a way of lowering prices at the expense of the firms providing the service. The regulatory authorities can also seek personal gains such as monetary incentives or political incentives therefore implementing policies that cater to these needs at the expense of the public interest. Public policy theory of regulation highlights the importance of setting up structures that aim to remedy this problem. This can be achieved by creating a number of agencies that monitor each other in a cycle. This guarantees that no one agency has absolute power.

1.1.3 Deregulated(Competitive) Electricity Markets

In contrast to the regulated market, deregulated markets have multiple utilities that have divested ownership of the electricity supply chain. This includes generation, transmission and distribution. Utilities compete for prices and consumers. In deregulated markets, the utility has an incentive to sell power to not only the consumers near the power plant but to extend its market to long distance consumers. Allowing trading of electricity can cause a strain on the transmission grid designed for local monopolies, however in the case of low network access, the utility has an incentive to build the infrastructure to facilitate expansion. Competition provides an incentive to firms to respond to consumer needs, reduce operational costs, and compete on the basis of prices. This influences utilities to be innovative in order to gain competitive edge over peer companies. This edge may be temporary since the other firms will respond accordingly. However, it helps the competition with innovation which in turn helps consumers and the environment. Some of the benefits of electricity deregulations include the following:

- Provision for competition- Deregulation ensures that all companies have an equal opportunity to provide electricity to consumers. Creating a level playing field ensures that no one firm has exclusive right to serving consumers and it also eliminates some barriers to entry.

- Lower prices for consumers- The presence of competition allows the consumers to seek cost competitive alternatives. This results in reduction of costs on the consumers side.

- Improved service reliability - In the presence of a monopoly , consumers cannot switch to a different provider once the monopoly proves to be unreliable. In the presence of competition, utility providers are forced to take into account the possibility of losing customers due to poor service reliability. This creates accountability on the part of the firms.

- Environmental benefits - The presence of competition forces the utilities to explore efficient ways of producing electricity in order to lower the costs. This means improving technology, thus reducing environmental damage and the firms reduce the costs of environmental taxes etc. All these factors result in cleaner generation of energy.

1.1.4 Externalities

One of the resultants of fossil fuel electricity generation is pollution. This is especially true in thermal power plants that use fossil fuels. The burning of fossils fuels emits pollutants such as $S0_2$, CO_2, $N0_x$. These gases lead to acid rain and cause different ailments. [60] shows that air pollution has negative effects on health and contributes to mortality rate, cardiovascular and respiratory illness. He quantified the impacts of coal operated power plants in South Africa to be valued at $ 2.4 billion annually. The cost of the impacts caused by the coal fired plants accumulates yearly during the lifetime of the plant. With average lifetimes of nearly 20 years for thermal power plants, the costs on the the population becomes very large [60]. In recent years there has been a push amongst nations to gradually transition to greener energy sources as the consequences of climate change have become more apparent. According to the World Bank environmental indicators, the world combined released 4.972 metric tons per capita in 2014. With the exception of South Africa, African and developing countries emit less $C0_2$ for a unit of GDP than the world average. This is a result of the lower levels of industrialization in developing countries and lower levels of electricity access. The level of $C0_2$ emissions is directly proportional to the levels of electricity demand. Therefore the lower levels of demand in developing and African countries explain the low $C0_2$ emissions per capita. Both academics and policy makers are concerned about the best way to reduce greenhouse effects and minimizing the economic effects that can arise from such action. There is a need to find an efficient way to deal with this issue.

Tradable Permits vs Emission Taxes

On December 10, 1997, 160 countries signed the Kyoto Protocol agreement on limiting emissions of greenhouse gases [125]. This set in motion the debate on how to efficiently achieve the reduction in pollution in different economies. Economic literature draws a clear distinction between command and control approaches (CAC) and market-based incentives (MBI), with the latter being preferred over the former [125]. The high costs of monitoring in the CAC approach makes it less desirable. Two MBI instruments have been used as a control strategy for green house emission reduction: enviromental taxes and tradable permits have been adopted by different countries over the past two decades. The main challenge to policy makers is knowing which instrument to adopt and under what conditions will the instrument be more efficient. There is established economic literature that details the efficient conditions to implement either the environmental tax or the tradable permits.

Environmental Taxes

Environmental taxes are also known as Pigouvian taxes. This is a tax that is charged on any market activity that imposes costs on the society (negative externalities). The intent of this tax is to move the market from an inefficient point to an efficient point where the cost to society is lower than the inefficient point. In energy economics, this can be achieved by levying a carbon tax on power suppliers. The tax levied on the suppliers needs to be equal to the total damage caused by the extra unit of emissions. This means that the tax needs to be a true reflection of the cost to society, therefore the power supplier has an incentive to reduce emissions to the point where a unit reduction in emission is equal to the social damage [60]. According to Van Heerden the Pigouvian tax has four effects on an economy [58];

1. taxes result in an increase in production costs in energy intensive industries, thus reducing export demands of energy intensive goods , making imports a more attractive alternative. This reduces the output in energy intensive trade related sectors. There is also a shift of labor supply from energy intensive sectors to less energy intensive sectors.

2. Increase revenue collected by the government, however this revenue needs to be distributed in order to avoid a reduction in purchasing power, thus resulting in a decrease household consumption.

3. Cause a decrease in GDP. This is because the tax causes an increase in prices, thereby increasing inflation. The increase in costs reduces consumption, therefore reducing output levels by industries. This results in a decrease in the GDP. This directly affect the unskilled workers whose wage-price ratio goes down as inflation increases.

4. Cause substitution from energy and energy rich commodities to sectors with low energy consumptions. This reduces demand in energy, therefore resulting in a decrease in greenhouse gas emissions.

Setting up an efficient tax regime requires the regulator to have a lot of information about the utility company. The regulator needs information about the marginal abatement costs (MAC) and marginal benefits cost (MBC) of the utility. Without this knowledge it becomes challenging for the regulator to set up a tax level that will achieve the efficient levels of emissions.

Tradable permits

The Tradable permit system requires the regulator to investigate and set a cap on the levels of pollution allowed for a specific industry. In this case it is the levels of pollution allowed for electricity generation. Once the pollution cap is established, the regulator issues permits that amounts to the cap limit e.g. a cap of 3 000 000 tonnes of $C0_2$ will require 3 000 000 permits. These permits are either distributed to the participating firms or sold in a blind auction (highest bidder wins). No firm is allowed to emit pollution without acquiring the equivalent number of permits. After acquiring the permits, a firm can buy or sell permits to/from other firms. Tradable permits can induce innovation and development as firms seek ways to minimize costs. A potential shortfall of tradable permits is in dealing with market power. Koustaal [**?**]and Xepapadeas[75] separately established that firms when firms behave as price setters , the gains of tradable permits are lost . The following table summarizes the main finding of the discussion provided by Norregaard and Reppelin-Hill [125].

Table 1.1: Summary of Efficiency Considerations and Market Structure

Market Structure	Emission Tax	Tradable Permits
Perfect Competition	Efficient	Efficient
Noncompetitive market in the output market	Efficient can be achieved by suitably adjusting the Pigouvian tax but only if firms are all identical	Inefficient but literature suggests that efficiency losses may be smaller than under an emission tax(when firms have different pollution technologies).
Noncompetitive market structure in the permits market	N.A	Inefficient

Source = Norregaard and Repellin-Hill 2000

The importance of privatization is supported by the inefficient levels that are achieved by both the emissions tax and tradable permits in a monopolistic market [47]. By introducing competition, the market becomes efficient under both the emission tax or the tradable permits. It is important to note that the environmental tax achieves a social optimum [68] when the firms causing pollution are identical, i.e, use similar technology for electricity production. In the case of dissimilar technologies, only the firm specific environmental tax achieves the social optimum [68].

1.1.5 Current State of Electricity Markets in Developing Economies

It is a challenge for policy makers to design an efficient market structure for a region that faces deficiencies in utility coverage, service backlogs of grid repairs or expansion, unique socioeconomic characteristics, unique institutional endowments and weak economic regulatory mechanisms [81]. Economic regulation of utilities include issues such as pricing, cost of service, investments , quality (this includes service obligations and set service standard) and rate of returns on assets [4]. Most countries in the developing world have a monopolistic design for power markets. This can be through government policy or a superior utility provider that imposes a monopoly. The lack of competition, brings about challenges in the continuity of service delivery and the quality of services provided. It also provides challenges in establishing economically efficient prices for the utility. Government regulation can make it difficult for the utility provider to make profitable investments in enlarging its network. Also, the utility provider can charge exorbitant prices because of its dominant control on the sector. These challenges make it difficult for consumers in these markets to have access to reliable and efficient services. This in turn affects the economic development of these countries since power supply plays a critical role in the efficient operation of industry and service systems. All challenges raised in this section can be explored with focused research on each challenge. However, this dissertation focuses on understanding the pricing dynamics due to entry into the market by a competitive firm. The World Bank (2008) showed that , in Sub-Saharan Africa, 26% of the population has access to electricity, 1% to fixed telephony, 14% to mobile , 60% to water, and 34% to rural transport[73].

Most Sub-Saharan African countries like Zimbabwe, Angola and South Africa heavily depend on fossil fuels for electricity generation. Mainly because it is cheaper and fossils are readily available in most of these countries. However, fossils such as coal lead to large emissions of Carbon-dioxide and Sulphur dioxide. These lead to acid rain, which affects agricultural production. Most of Sub-Saharan Africa heavily relies on subsistence and commercial farming for income generation on a household and national level respectively. This leads to a reduction in social welfare and quality of life. The calls for a cleaner earth and the advancements in technologies used to extract and use renewable energy sources has changed energy economics. There is a need for an active investigation into how to efficiently incorporate different sources of energy on the same grid to increases consumer utility. The research on electricity markets is therefore important in addressing such issues especially given the World Bank's target of 92% electrification worldwide by 2030 [73]. For such rates of electrification to be achieved, there is a high need to understand methods to boost investments for electrification in developing countries since these lag behind the rest of the world in terms of electricity access. Often the regulatory uncertainties in most developing countries have been cited as one of the many causes for under investment in infrastructure development [81]. However, research in optimal investing can be used by investors to minimize risk and still be profitable in uncertain markets. Therefore, the use of both optimization models and economic techniques can be highly valuable in helping increase investment in infrastructure development projects in developing countries.

1.1.6 Motivation and Significance

The presence of adequate and efficient infrastructure is widely recognized as an important factor in the quest for economic growth. This recognition comes from both policy makers and academics who work on understanding the role of infrastructure in economic growth [9, 114, 11]. While most developing countries face the problem of infrastructure development, sub-Saharan Africa is consistently ranked bottom in terms of infrastructure performance. There are a number of studies that focus on either forecasting the infrastructural needs or comparative understanding of the effects of infrastructure deficiencies in Sub-Saharan Africa. [44] use an econometric approach in estimating the demand for electricity and telephony, and used this to project the dollar investment needs in electricity and telephony for South Africa . This approach can be extended to any developing country. Luis Servén at the WBG has done extensive work on providing empirical evaluations on the effects of infrastructure development to the growth of an economy and income distribution [13]. While these studies provide useful information to policy makers, they do not address the question of how to meet these needs in the long term. While this project does provide a framework that can be used to meet the infrastructural needs of the future, it provides an analytically tractable long term pricing path for firms that seek to maximize long term profits and network size. It also provides a policy framework for policy makers environmental and social goals.

The dependence of productivity and social welfare on the access of regular and uninterrupted electricity supply are well established. Both factors contribute to economic development and environmental sustainability, therefore uninterrupted access to electricity supply is important for economic growth. The research methods applied on electricity markets need not be limited to just electricity markets. These methods can be extended to any infrastructural needs for developing and developed countries. Optimal control theory and differential game theory are applicable in scenarios that require finite or infinite horizon planning and the existence of players interacting strategically.

As the demand for electricity increases and the access rates improve, the amount of greenhouse gas emitted into the atmosphere increases. It becomes the responsibility of policy makers to craft policies that improves the investments into electricity while minimizing the amount of pollution from electricity generation. These types of problems have been studied in literature as the **Social Planners Problem**.

This dissertation focuses on the implementation of optimization methods and economic theory on designing an efficient market structure. Specifically, the main focus is on developing countries whose energy markets are undergoing privatization. The goal is to formulate the design of an optimal pricing path for new market players whose objective is to maximize long-run profits by optimizing network size. The market entrants face a state utility that maximizes long run profits. In other words, the pricing structure of the incumbent is deterministic. Entrant players can use this analytically tractable framework for optimal pricing and profit maximization.

This framework can also be useful in informing market players on decisions on infrastructure investments. The framework provides a set-up of market structures that allows the fulfillment of infrastructural needs of the future by empowering both the investor and the policy makers. The aim is to help accelerate electricity infrastructure development in these countries. It is also important to quantify the benefits of establishing competitive markets and compare the performance of electricity markets in different economic regions. Using an econometric approach, this dissertation provides an approach to measure the effects of privatization and competition. This provides an objective measure that can be used to shape economic policies in developing economies.

1.1.7 Research Purpose and Objective

The goal of this dissertation is to use optimal control theory and differential games to analyze the electricity markets in developing countries. The main contribution will be providing a framework for introducing competition in the electricity markets of developing countries. This work will also add to the already existing literature of environmental taxes as an instrument to reducing pollution. To date, there is little or no literature that models environmental taxes in a differential game structure for electricity markets in developing countries nor the introduction of competition by the entry of a competitive firm that seeks to maintain its market presence by implementing profit maximizing strategies. There exists a clear distinction between the developed countries' electricity markets and developing countries' markets. These differences can be summarized as:

- Nature of market design(Monopolistic vs Competitive),
- Level of electricity access,
- Government efficiency, and
- Infrastructure development.

The focus on competitive markets stems from the possible benefits that these markets provide; the competitive pressure can result in lower prices, efficient technology and increase in levels of electricity access. These direct consequences of competition are the targets of policy makers in developing and developed electricity markets. The following subsections summarize the research questions explored. Listed below, the research questions include :

- Can firms achieve optimal pricing paths in privatized underdeveloped networks,
- What is the optimal taxing strategy to increase competitiveness of green utilities,
- Can subsidies minimize entry deterrence in the presence of a dynamic pricing cap, and
- Are the effects of privatization and competition in electricity markets measurable.

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1.2 Organization of Dissertation

The first chapter provided the background and the significance of continued research in the design of electricity markets in developing countries to improve infrastructure development, access of electricity, environmental protection policies and pricing methods. It also provides the research purpose, motivation,and research contributions. The remainder of the dissertation is organized into seven chapters, as outlined below;

Chapter 2: Literature Review

This chapter reviews the literature related to the focus of this study, this includes (1) pricing methods that are employed in the electricity markets of developing countries (2) Optimal control theory and its applications to market share competition (3) Game theory methods, specifically the extension of optimal control theory to differential games.

Chapter 3: Research Methods

This provides the methods that are used in analyzing the proposed research questions. This includes methods used in solving differential games i.e Open Loop Nash Equilibrium, Open Loop Stackelberg Equilibrium, Markovian Nash Equilibrium and Non-Markovian Nash Equilibrium

Chapter 4: Pricing Dynamics of Electricity in Privatized Competitive Markets with Developing Networks

This chapter provides an analysis of the pricing path that is followed by a profit maximizing state utility that is facing a serious entrant firm that is also maximizing its long run profits. The pricing path will be influenced by the parameters used in modeling the cost function and the state dynamics.

Chapter 5: Optimal Taxing Strategy to Increase Competitiveness of Green Utility Suppliers: A Theoretical Framework

This chapter provides an analysis on the use of a taxing strategy in order to help green utilities becomes sustainable market players. Green utilities face high investments cost that makes them less competitive in terms of price relative to conventional energy utilities. A policy maker that

Chapter 6: Measuring the effects of Competition and Privatization in Electricity Markets: An Econometric Approach

The focus of this chapter is the validation of the models suggested in the previous chapters by using real world data. This data will come from developing countries that have made the transition from regulated market structure to deregulated market.

Chapter 7: Conclusions and Future Work

This chapter includes the summary of the research analysis in the previous chapters, contributions and the advantages of the proposed methods. It also provides a description of areas for future research is discussed. This consists of areas where the research can be expanded either by using newer methods or an extension of some of the models used in this dissertation.

Chapter 2

Literature Review

This chapter provides a review of the literature that is relevant and closely related to the topics discussed in this research. There is a thorough discussion on the evolution of the methods of pricing electricity in regulated or semi-deregulated markets.The review also provides an insight on the implications of these methods to economic growth, social welfare and policy formulation in these markets. Finally, this chapter provides a discussion of the methods used in formulating and analyzing pricing models in a deregulated market. Specifically, it provides an overview of optimal control theory and the extension of this theory to differential games using the principles of game theory.

2.1 Pricing Electricity

Pricing public utilities is a challenge especially in developing countries. The goal of pricing is to allow efficient allocation of resources in the system. The firms are interested in profitability while government/ policy makers are interested in social policy and political objectives . It is difficult to find a balance between the two different objectives, since developing countries often lack the necessary conditions to achieve an efficient market where $P = MC$. In many developing countries, there exist state owned utilities that will implement prices, where $P < MC$ for political reasons. The following methods have been used in the past to determine the prices of electricity in the developing countries.

- Cost Recovery Pricing- This requires the setting of a price that allows the service provider to recover its investments costs and also gain an acceptable return on investment. This can also include depreciation costs. This approach is often used by state controlled utilities in situations where the value of assets is significantly greater than the additional investments required in future periods. A regulatory board determines a fair return bounds on the investments by considering both social and political objectives. It is easier to calculate the cost of production once a fair rate of return has been determined The price allowed becomes;

$$P = \mu(AC) \quad 1 \leq \mu \leq b$$

Where AC = average cost of energy generation, μ = allowable mark up percentage and b = the bounds on the allowable mark up.
A market that employs this pricing method creates a strong barrier to the introduction of competition. It also does not reward for efficiency and performance since the return is set based on the level of fixed assets of the utility provider. The lack of performance based rewards leads to the disadvantages similar to that of a monopoly discussed previously [74].

- Marginal Cost Pricing- Prices of the electricity are set as equal to the marginal cost incurred by the utility to provide electricity to each additional consumer. The limitation of marginal cost pricing is that it does not take into account capital cost in the short run [64]. Energy investments are long term investments, therefore marginal costs should include the costs of expanding and capacity or improving technologies used in the generation of power.

- Opportunity Cost Pricing-The utility analyzes how much it would charge for its service if it was located in a different country. This method provides a good check for policy makers if the markets chosen have similar characteristics to the market under study. Since most countries do not observe the same market conditions this method does not provide a good check for internal pricing. For example, Zimbabwe and South Africa have some of the world largest coal reserves , but there is a large disparity between the level of coal production in both countries. This means that using the opportunity cost pricing method with each neighbor as a reference point is not an effective pricing benchmark for either country. The country specific differences means that the prices charged do not always reflect opportunity cost for a player in a different market [74].

- Market Pricing- This pricing method is used when there are multiple players in the market. The price converges to an optimal price for the allocation of resources in the market. Economic theory shows that this is the most efficient method of pricing. However, market pricing does not always converge to affordable prices for consumers[74]. This poses a problem for policy makers in developing countries whose objective is to provide a structure for regular and affordable electricity services to the consumers. However, it reflects scarcity of resources which should be incorporated into policy making.

2.2 Optimal Control and Differential Nash Games

Optimal Control is the process of determining control and state trajectories for a dynamic system over a period of time to satisfy a given objective function i.e. minimization or maximization. Optimal control theory was developed by Russian mathematicians. One of the main contributors to optimal control theory is Pontryagin who developed the *Maximum Principle*. Economists like Dorfman [18] extended optimal control theory to economic applications. Optimal control optimization has the following advantages;

- Allows long run planning,
- Allows flexibility, and
- It is commonly used in several industries such as **electricity**, transport, retail and entertainment.

The following is a general optimal control problem formulation as defined in [17] ;

$$\max_{u(t)} J = \int_0^T F(\mathbf{x}(t), \mathbf{u}(t), t)dt + S[\mathbf{x}(T), T]$$

$$\text{s.t}$$

$$\dot{x}_i(t) = f_i(\mathbf{x}(t), \mathbf{u}(t), t) \qquad i = 1, ..., n; \quad \text{(Transition Equation)}$$

$$x_i(0) = x_{i0} \qquad i = 1, ..., n; \quad \text{(Initial Conditions)}$$

$$x_i(T) \geq 0 \qquad i = 1, ..., n; \quad \text{(Terminal Conditions)}$$

$$\mathbf{u}(t) \in \Re^n \quad \text{(Feasible set)}$$

Where,

$\mathbf{x}(t)$ = is an n-vector of state variables($x_i(t)$). The state variables describes the state of the system at any given point in time. We have $\frac{dx_i}{dt} = \dot{x}_i$
$\mathbf{u}(t)$= is an n-vector of control variables. The optimization problem is solved over these variables.
$F(.)$ is the objective function.
$f(.)$ is the transition function for each state variable.

The Pontryagin maximum principle is used to solve the optimization problem by defining a Hamiltonian function,H. The following is the Pontryagin's theorem as presented in [17]

Theorem 1 *For $\boldsymbol{x}^*(t)$ and $\boldsymbol{u}^*(t)$ to be optimal for (1), it is necessary that $\exists$ a constant λ_0 and continuous functions $\Lambda(t) = (\lambda_1(t), ..., \lambda_n(t))$, where $\forall\ 0 \leq t \leq T$ we have $\lambda_0 \neq 0$ and $\Lambda(t) \neq 0$ such that $\forall\ 0 \leq t \leq T$;*

$$H(\boldsymbol{x}^*(t), \boldsymbol{u}, \Lambda(t), t) \leq H(\boldsymbol{x}^*(t), \boldsymbol{u}^*(t), \Lambda(t), t)$$

where the Hamiltonian function H is defined as;

$$H(\boldsymbol{x},\boldsymbol{u},\Lambda,t) = \lambda_0 F(\boldsymbol{x},\boldsymbol{u},t) + \sum_{i=1}^{N} \lambda_i f_i(\boldsymbol{x},\boldsymbol{u},t)$$

with the exception at the points of discontinuity of $\boldsymbol{u}^*(t)$*,*

$$\frac{\partial H(.)}{\partial x_i} = -\dot{\lambda}_i(t), \quad i = 1,..,n.$$

Furthermore , $\lambda_0 = 0$ *or* $\lambda_0 = 1$ *and, finally , the following transversality conditions are satisfied;*

$$\lambda_i(T) \geq 0, \quad \lambda_i(T)x_i^*(T) = 0, \quad i = 1,...,n.$$

The Hamiltonian defined above has to be concave in **x** and **u** for a maximization problem, the necessary conditions for a maximum are :

$$\frac{\partial H(.)}{\partial u_i} = 0, \quad i = 1,..,n;$$

$$\frac{\partial H(.)}{\partial x_i} = -\dot{\lambda}_i(t), \quad i = 1,..,n.$$

$$\frac{\partial H(.)}{\partial \lambda_i} = \dot{x}_i(t), \quad i = 1,..,n.$$

$$\lambda_i(T) \geq 0, \quad \lambda_i(T)x_i^*(T) = 0, \quad i = 1,...,n.$$

The optimization problem above may include other transition equations, we have;

$$\max_{u(t)} J = \int_0^T F(\mathbf{x}(t),\mathbf{u}(t),t)dt + S[\mathbf{x}(T),T].$$

s.t

$$\begin{aligned} \dot{x}_i(t) &= f_i(\mathbf{x}(t),\mathbf{u}(t),t) && i = 1,....,n; \\ \dot{s}_i(t) &= s_i(\mathbf{x}(t),\mathbf{u}(t),t) && i = 1,....,n; \\ x_i(0) &= x_{i0} && i = 1,....,n; \\ x_i(T) &\geq 0 && i = 1,....,n; \\ & && \mathbf{u}(t) \in \Re^n \end{aligned}$$

We define the present value Hamiltonian equation;

$$H(\mathbf{x},\mathbf{u},\Lambda,\Omega,t) = \lambda_0 F(\mathbf{x},\mathbf{u},t) + \sum_{i=1}^{N} \lambda_i f_i(\mathbf{x},\mathbf{u},t) + \sum_{i=1}^{N} \omega_i s_i(\mathbf{x},\mathbf{u},t)$$

The Hamiltonian defined above has to be concave in **x** and **u** for a maximization problem , the necessary conditions for a maximum are :

$$\frac{\partial H(.)}{\partial u_i} = 0, \quad i = 1,..,n;$$

$$\frac{\partial H(.)}{\partial x_i} = -\dot{\lambda}_i(t), \quad i = 1,..,n.$$

$$\frac{\partial H(.)}{\partial s_i} = -\dot{\omega}_i(t), \quad i = 1,..,n.$$

$$\frac{\partial H(.)}{\partial \omega_i} = \dot{s}_i(t), \quad i = 1,..,n.$$

$$\frac{\partial H(.)}{\partial \lambda_i} = \dot{x}_i(t), \quad i = 1,..,n.$$

$$\lambda_i(T) \geq 0, \quad \lambda_i(T)x_i^*(T) = 0, \quad i = 1,...,n.$$

The concavity of the Hamiltonian function can be tested by checking the definiteness of the Hessian matrix. The Hessian matrix is defined as follows;

$$\hat{H}_i = \begin{bmatrix} H_{x_i u_i} \end{bmatrix} \quad \forall x_i, u_i \quad i = 1,...,n$$

2.3 Optimal Control: Pricing Strategy under Monopolistic Design

One of the first extensions of optimal control theory to optimal pricing strategies was done by Gaskin. Gaskin proposed an intertemopral framework for pricing strategy for a dominant utility(or cartel) that is faced by a competitive fringe [55]. In this model, high prices set by the dominant firm causes an increase in the sales by the entrant firm. Gaskin models the the present value of the dominant firm profits as follows;

$$\max_{u(t)} J = \int_0^{\infty} [p(t) - c][f(p) - x(t)]e^{-rt} dt. \tag{2.1}$$

s.t $\quad \dot{x} = k(p(t) - \bar{p}), \quad x(0) = x_0$
Where, $\quad x(t)$ = sales by fringe competitor, $p(t)$ = the price set by the dominant firm, $f(p)$ = market demand , and c marginal cost of production.

This model assumes that;

1. The fringe competitor is a passive player, i.e, the fringe is a price taker,

2. The fringe competitor has constant average and marginal costs of production, and

3. The dominant utility has a cost advantage.

Extensions of this model for the monopolistic firm in the presence or absence of competition can be seen in [24, 25, 26, 27]. The majority of these models have applications in advertising and supply chain management etc., and these are of marginal concern to the question posed in this dissertation. Chisari and Kessides, also extend the Gaskin Model to model an optimal pricing strategy of an electricity utility firm that is located in a developing country [81]. The assumption of an underdeveloped network, poor regulatory reforms, electricity theft are all included in the model formulation. The following models the present value profit function of the dominant utility;

$$\max_{p(t)} \Pi(t) = \int_0^{\infty} e^{-rt}[PN - C(N)]dt \tag{2.2}$$

s.t $\quad \dot{N} = \gamma[\xi(N) - P], \quad N(0) = N_0$

Where $\quad \xi(N)$ = unit cost of the fringe competitor, $P(t)$ = the price set by the dominant firm, N = Network size of the incumbent , and $C(N)$ = Cost of energy production.

The unit cost is defined as;

$$\xi(N) = \xi_0 + \xi N$$

The unit cost of the the fringe utility as the network size of the incumbent increases. The dependence of the fringe costs on the size of the incumbent's network size, takes away the strategic response that can be implemented by the fringe utility rendering the fringe passive. This lack of strategic interaction between the two firms means that the incumbent firm has a strategic advantage as it can find an optimal pricing path that will drive the fringe out of this market and return to monopoly status. The set up in this project introduces a strategic interaction between firms, so that it is the market that decides the price and each firm can strategically respond to the market conditions. This response is captured in the equation of motion of the optimal problem for each firm. The equation of motion above is adjusted as follows;

$$\dot{N}_i = \gamma[P_j - P_i], \quad N_i(0) = N_0$$

Each firm controls its price,P_i, therefore can strategically respond to the markets conditions. No firm has a strategic advantage, and the firms compete on technology and efficiency in order to minimize operational cost, thereby charging lower prices.

The cost function $C(N)$is defined as;

$$C(N) = F + aN + c[\rho M + (1-\rho)N]^2 + \phi \dot{N}^2 \quad a > 0, \quad c > 0 \quad F \geq 0 \tag{21}$$

Where F are the fixed costs for each utility provider, $\phi \dot{N}^2$ is the adjustment cost in network size [46, 57], and c are the marginal costs.

While this cost function captures the costs due to energy production and theft, it needs to be

extended to capture the current conditions in which utilities operate under. These extensions, include but are not limited to environmental tax, abatement costs, theft under multiple players etc., This chapter extends this cost function to include the dynamics between the dominant utility and a competitive firm, it also includes the presence of an environmental tax as a cost to the firms in the market.
This optimal control model assumes that,

1. The fringe competitor is a passive player, i.e. the fringe is a price taker,

2. The fringe is assumed to have increasing marginal cost as the incumbent increases its network size, and

3. The dominant utility has a cost advantage.

In this case, prices above the unit cost of the fringe competitor by the incumbent utility results in the reduction of its network size. Unlike in the Gaskin's Model, Chisari and Kessides assume that the fringe competitor has increasing marginal costs instead of constant average and marginal costs i.e., as the the network size of the dominant utility increases , the unit costs of production for the competitive fringe increases. Therefore, by setting prices below the fringe marginal cost, the incumbent makes it more difficult for the competitor to stay in the market. This model provides an analytically tractable framework for analyzing the optimal pricing strategy for an electricity utility supplier facing a competitive fringe and an underdeveloped network.
The obvious short fall of all the models described above is the limited consideration of the optimal pricing strategy from the perspective of the incumbent firm. It is not satisfactory to assume that an entrant firm or a fringe does not seek an optimal pricing strategy. This is of particular concern when moving from a fringe supplier to a serious market entrant that is likely to prove sustainable in terms of presence. This criticism of the Gaskin model is summarized by Gilbert [56] as follows; "A main criticism of Gaskins' model is that entry is not an equilibrium process. The entry equation is not the result of optimizing decisions by a pool of potential entrants, but is specified exogenously in the model. The incumbent firm (or cartel) is presumed to act rationally, choosing a price policy to maximize present value profits. But there is no corresponding maximization problem for the firms that make up the flow of entry into the industry. Firms are not symmetric in Gaskin's model in their degree of rationality. Only the incumbent firm(s) can boast an identity in the Gaskin's model. Entrants are relegated to a nameless component of an output flow."

In order to address the criticism of the Gaskin Model, it is necessary to move from a fringe competitor to a serious entrant firm that is considered as a profit maximizing firm. This requires models that also model the objective function of the fringe competitor under a specified control. The following section discusses such models in detail.

2.4 Differential Nash Games: Pricing Strategy under Competition

In order to address the criticism of the Gaskin Model, where the entrant firm is treated as a price taking player, there is a need to model the entrant firm as a strategic firm. This requires the modeling of the entrant firm's problem as an optimal control problem. Modeling the entrant firm as a strategic player induces strategic interaction between the entrant and the dominant firm. The goal for each firm is to establish an optimal strategy to achieve its own objective function in the presence of another firm that is also seeking an optimal strategy to achieve its objective. Game Theory provides a theoretical basis of understanding strategic interactions between different *decision makers* or *players*. In the context of this research, *decision maker* or *players* refers to the entrant firm , dominant firm or policy maker and all the players interact strategically and are assumed to be rational.

A game is defined as *dynamic*, if the order in which strategies are implemented by the players is important to the outcome of the game. The game is also defined as *non-cooperative* if each player solely focuses on achieving its objective which is a conflicting objective to that of the other player. The theory of differential games is derived from optimal control theory and game theory. Differential games have the following characteristic [32];

- Interdependence: i.e, the decision by a single player influences the achievement of the objective by the player and the other players involved,
- Strategic : All the players are assumed to be rational, i.e, they consider the influence of their actions on their objective function and the actions of other players on their own objective function. The actions taken by each player becomes a recursive best response to the best response of the other players, and
- Time : The objective function is either maximized or minimized as an accumulation function over a period of time, this can be a finite or infinite time horizon.

The following table summarizes the classification of games with single or multiple players as in [33];

Table 2.1: Game Classification

	One Player	Multiple Players
Static	Mathematical Programming	(Static) game theory
Dynamic	Optimal Control Theory	Dynamic(and / or differential) game theory

The literature of the structure of a differential game is well developed. Similar to game theory, differential games require a well defined structure for an effective analysis of the game. The following sections develop the general set up of a general differential game in the form of the objective function, elements of the game and information structure.
A differential game is defined as an interaction between a set of N players, $N = [1,2,...,N]$. Each player $i \in n$, has a vector of control u_i(t) $\in U_i \subseteq \Re^{m_j}$ where U_i is a set of admissible control values for player i. The control, u_i(t) , is also a function of the control of the other players. This creates the strategic interaction between the players involved. Each player at any given time,t is in a state $\mathbf{x}(t) \in X \subseteq \Re^n$ where X is the set of admissible states. The rate of change of the state variables is determined by the equation of motion, which is a system of differential equations;

$$\dot{\mathbf{x}}(t) = \frac{d\mathbf{x}}{dt} = f(\mathbf{x}(t), \mathbf{u}(t), t), \quad \mathbf{x}(t^0) = \mathbf{x}^0 \tag{2.3}$$

A payoff function for player i, $i \in n$ is defined as follows;

$$J_i = \int_{t^0}^{T} g_i(\mathbf{x}(t), \mathbf{u}(t), t) + S_i(\mathbf{x}(T)) \tag{2.4}$$

where g_i is player $i's$ instantaneous payoff function and S_i is the terminal payoff.
It should be noted that the time horizon, T, can either be finite or infinite. The difference between the two is established by the transversality conditions for the problem. The instantaneous payoff can be discounted for time, this is common in infinite horizon problems. The information structure is defined as the knowledge that is available to player i when he/she selects $u_i(t)$ at t. The following information structures are used in the analysis of differential games;

- Open Loop: This is a game where the players cannot observe the play of their opponents before they make their own decision.

- Markovian(Feedback): All the players can observe the state variable of the other players and make its own decision based on these observations.

The timing of players decisions also determines the nature of the game. There are two types of decision making we consider;

- Simultaneous - This means that both players choose their strategies concurrently. Each player solves its own optimal control problem by choosing the best response assuming the best responses from the other players.
- Sequential - The players choose their optimal strategies in an ordered manner. The players are defined as a ”leader” and a ”follower”. The follower solves its optimal problem first similar to the simultaneous case. The sequential differential game with a defined leader and a follower is known as the **Stackelberg differential game.**

The earliest applications of differential game theory were developed for military applications by R. Isaacs in the late 1950 to early 1960s. The applications have since been extended to other fields such as supply chain, environmental economics, marketing, finance etc.. The following table gives a summary of some of the applications of differential games and the solution concepts that have been used in the literature.

Table 2.2: Differential Game Applications

Paper	Dynamics	Control	Simultaneous decision	Sequential decision	Solution
Eliashberg and Steinberg(1987) [34]	Seasonal	Production rate, Price	No	Yes	OLSE
Desai (1992) [35]	Seasonal	Production rate, Price	No	Yes	OLSE
Desai (1996) [36]	Seasonal	Production rate, Price	Yes	Yes	OLNE , OLSE
Jain and Chintagunta(2002) [37]	NA dynamics	Ad.Effort , Price	Yes	No	OLNE, FNE
Fruchter and Messinger(2003) [38]	General	Ad. effort , Price	No	Yes	FSE
Kogan and Tapiero(2007a)[39]	General	Price, Production rate	No	Yes	OLSE
Kogan and Tapiero(2007b)[39]	General	Processing rate, Production rate	No	Yes	OLSE
Kogan and Tapiero(2007c)[39]	General	Price, order quantity	No	Yes	OLSE
Kogan and Tapiero(2007d)[39]	General	Price, order quantity	No	Yes	OLSE
Kogan and Tapiero(2007e)[39]	General	Price	No	Yes	OLSE
He and Sethi(2008)[40]	Bass type	Price	No	Yes	OLSE
Fanokoa, Telahigue and Zaccour (2010) [41]	General	Production policy	Yes	No	FNE
Novak , Feichtinger and Leitmann(2010)[42]	General	Resource allocation, rate of attack	Yes	Yes	OLNE, OLSE

OLSE = Open Loop Stackelberg Equilibrium , **0LNE** = Open Loop Nash Equilibrium

FNE = Feedback Nash Equilibrium, **FSE** = Feedback Stackelberg Equilibrium

Chapter 3

Methodology: Solving Differential Games

This chapter presents theoretical definitions of the different equilibriums that can be achieved when solving differential games. Each equilibrium is achieved under specific conditions; these conditions are explicitly stated in each section in this chapter.

3.1 Nash Equilibrium

A Nash *solution* is defined as a set of N admissible trajectories for (2) i.e.

$$u^{1*}, u^{2*}, ..., u^{N*}$$

, These trajectories have the property that;

$$J_i(u^{1*}, u^{2*}, ..., u^{N*}) = \max_{u^i \in U_i} J_i(u^{1*}, u^{2*}, ..., u^{(i-1)*}, u^i, u^{(i+1)*} u^{N*}) \tag{3.1}$$

for $i = 1, 2, ..., N$ In order to satisfy the necessary conditions of a Nash equilibrium solution for non-zero sum differential games, a clear distinction between closed loop controls and open loop controls is needed. This shows that each player chooses the best response given the best response of other firms that knows that other firms are choosing their best responses. This becomes a recursive best response of the best response of the best response and so forth.

3.2 Open Loop Nash Equilibrium

In an open loop equilibrium, each player solves its optimal control problem without observing the decisions of the other players. The players cannot observe the current state of the system. In this case the players decisions depend on the time , t, of the game and the set of feasible strategies available to the player. However each players assumes the best response from the other players. The equilibrium is achieved by recursively considering the best response of the best response of the best response and so forth for each player. In the electricity market this equilibrium is reached in the case where the players do not observe the current price set by the competitor until after the period is over. Since the players only observe the price of the previous period, it can assume that the open loop nash equilibrium will be reached when the current prices set by the market players is not influenced by the price it set in the previous period, i.e, the prices in each period are independent of each other.

The control n-tuple $\mathbf{u}^*(.) = (u_1^*(.),....,u_n^*(.))$ is an **open-loop Nash equilibrium** at $(t^0, \mathbf{x}^0)$ if the following holds [32]:

$$J_i(t^0, \mathbf{x}^0; \mathbf{u}^*(.)) \geq J_i(t^0, \mathbf{x}^0; [u_i(.), \mathbf{u}^*_{-i}(.)]), \quad \forall \mathbf{u}_i(.), i \in N \tag{3.2}$$

where $\mathbf{u}_i(.)$ is any admissible control for player i and $[u_i(.), \mathbf{u}^*_{-i}(.)]$ is the n-vector of control that is obtained when the $i-th$ component of $\mathbf{u}^*(.)$ is replaced by $\mathbf{u}_i$.
Each player solving the following optimal -control problem;

$$J_i = \max_{u_i(.)} \int_{t^0}^{T} e^{-r_i t} g_i(\mathbf{x}(t), [u_i(.), \mathbf{u}^*_{-i}(.)], t)dt + e^{-r_i t} S_i(\mathbf{x}(T))dt \tag{3.3}$$

S.T

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), [u_i(.), \mathbf{u}^*_{-i}(.)], t), \quad \mathbf{x}(t^0) = \mathbf{x}^0$$

3.3 Markovian Nash Equilibrium

In this case, the players can observe the state variable of the other players involved and make its own decision based on these observation. In electricity markets each player can have access to the network size of the all the competitor's since most utility companies provide this information. The following is the technical definition of the Markovian Nash Equilibrium.

The feedback n-tuple $\sigma^*(.) = (\sigma^{1*}, ..., \sigma^{N*})$ is a **feedback or Markovian-Nash equilibrium** (MNE) on $[0,T] \times X$if for each $(t^0, \mathbf{x}^0)$ in $[0,T] \times X$ the following holds [32];

$$J_i(t^0, \mathbf{x}^0; \sigma^*(.)) \geq J_i(t^0, \mathbf{x}^0; [\sigma_i(.), \sigma^*_{-i}(.)];), \quad \forall \sigma_i(.), i \in N \tag{3.4}$$

where $\sigma_i(.)$ is any admissible control for player i and $[\sigma_i(.), \sigma^*_{-i}(.)]$ is the n-vector of control that is obtained when the $i-th$ component of $\sigma^*(.)$ is replaced by σ_i.
In this case, define $\sigma^*(t, \mathbf{x}^*(t)) \equiv \mathbf{u}_i^*(t)$ where $\mathbf{x}^*(.)$ is generated by σ^* from $(t^0, \mathbf{x}^0)$ and solves the following optimal control problem;

$$J_i = \max_{u_i(.)} \int_{t^0}^{T} e^{-r_i t} g_i(\mathbf{x}(t), [u_i(t), \sigma^*_{-i}(t, \mathbf{x}(t))], t)dt + e^{-r_i t} S_i(\mathbf{x}(T))dt \tag{3.5}$$

S.T

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), [u_i(t), \sigma^*_{-i}(.)], t), \quad \mathbf{x}(t^0) = \mathbf{x}^0$$

Chapter 4

Pricing Dynamics of Electricity in Privatized Competitive Markets with Developing Networks

4.1 Introduction

There is a need to develop a theoretical framework to understand the intertemporal strategic interactions between a profit maximizing incumbent utility supplier facing one or more profit maximizing entrant utility supplier(s) at the early stages of transitioning from a monopolistic market to a competitive market.The majority of economic literature considers the Stackelberg, Betrand and Cournot competition models to determine the steady state prices and quantity levels in a duopoly or oligopoly market. This is informative when analyzing utilities in an already existing competitive market, it is not sufficient to understand the strategic interactions between an incumbent and an entrant firm at the onset of competition in the market. This paper addresses this gap in the literature by considering the pricing dynamics of two strategically interacting electricity utilities at the initial stages of competition. Understanding this theoretical framework is not an urgent matter in developed economies since competition already exists in these economies albeit at different degrees. However, this is not the case in most developing economies where the incumbent utility is often a dominant public monopoly. Thus, the general theoretical framework developed in this paper directly applies to developing economies where there is a need for a policy framework to encourage competition.

For the greater part of the twentieth century, electricity utilities in most countries operated as state controlled monopolies. The presence of state controlled monopolies often results in poor quality of service, low service penetration, and low capacity. These problems are more pronounced in developing countries where there are weaker regulatory mechanisms [81]. The developing economies also face the problem of low access levels to electricity supply; this is not the case for developed economies where both the rural and urban populations have 100 %

access to electricity.

Competition in electricity markets, in theory, should lead to improvement in the efficient use of resources, in the case of most electricity markets the use of coal and other fossil fuels, improve firms financial performance, improvements in service delivery, and capacity factors. The majority of European and North American markets have liberalized their markets to allow competition in the electricity markets. While the efficiency gains from adopting such a market structure are well documented in the electricity market literature, it is important to ask; Is competition in a developing economy different from competition in a developed economy? It might be the case that the fundamentals of competition are not different; however , the theoretical considerations for firms are different in these two markets. As mentioned earlier, the market in a developing economy poses some challenges to utility suppliers including: (1) acquiring optimal market share to maximize long run profits, (2) attracting new consumers that were not previously served by any market player and (3) underdeveloped infrastructure. In order to take all three conditions into consideration, there is a need to extend the theory of market entry in the presence of an incumbent player. Chisari 2009 extends Gaskin 1976 optimal control model of an incumbent facing competition from a fringe player. In both cases a fringe player is deemed to be passive, i.e, is a price taker that is not optimizing long term profits. Chisari extends this model to the electricity markets in developing countries by considering all the challenges mentioned above in the setting of a dominant monopoly incumbent that is facing a fringe independent power generator (IPP). The World Bank (2016) reported that there were 126 IPP's in Sub-Saharan Africa alone and this accounts for slightly more than 13 % of installed generating capacity in this region [136]. The same report shows that there exists strong governmental efforts in developing economies to encourage the growth of IPP's in order to keep up with the increasing demand as these economies expand. This has been indicated by the changes in legislation in some of the developing countries that encourage the participation of private players in the electricity markets. However, there is also a lack of a policy framework to actually achieve successful participation by IPP's [50]. The evidence above shows that government in developing countries encourages the participation of private players in the electricity market. This makes the case of short lived fringe market players less desirable. New investors will participate in a market that promises profitability and business sustainability. These two conditions show that the model proposed by Chisari, though insightful in the case of a monopoly that can meet demand increases and also increase the level of electricity access, it does not represent most cases in developing countries where the incumbent utility does not have the capacity to meet the current demand, let alone the increase in demand as is the case in most developing countries. This model is also not consistent with the introduction of legislation to encourage the participation of private players in the electricity markets as cited in [50].

It is a challenge for policy makers to design an efficient market structure for a region that faces deficiencies in utility coverage, service backlogs, unique socioeconomic characteristics, unique institutional endowments, and weak regulatory mechanisms [81]. Most countries in the developing world have a monopolistic design for power providers. This can be through government policy or a utility provider that imposes a monopoly. The lack of competition, brings about challenges in the continuity of service delivery and the quality of services provided. It provides challenges in establishing economically efficient prices for the utility. Government regulation can make it difficult for the utility provider to make profitable investments in enlarging its network. The utility provider can charge exorbitant prices due to its dominant control on the sector. These challenges make it difficult for consumers in these markets to have access to reliable and efficient services. The World Bank (2008) showed that, in Sub-Saharan Africa, 26% of the population has access to electricity, 1% to fixed telephony, 14% to mobile, 60% to water, and 34% to rural transport [73]. These low levels of access to utilities affects the economic growth of developing countries since power supply plays a critical role in the efficient operation of industry and service systems.

This paper presents a theoretical framework that extends the analytical framework presented by Chisari to create a general framework for designing electricity markets at the early stages of establishing a competitive market. The model presented introduces the entrant firm, IPP's, as a strategic player in the optimal model for profit maximization. This supports the current policy maker needs to keep IPP's in the electricity market and also provides a profit-based framework for investors to follow as they participate in the electricity markets of developing economies.

4.1.1 Pricing Methods in Regulated Electricity Markets

Pricing public utilities is a problem, especially in developing countries. The goal of pricing is to allow efficient allocation of resources in the system. Firms are interested in profitability while government/policy makers are interested in social policy and political objectives . It is difficult to find a balance between the two different objectives since developing countries often lack the necessary conditions to achieve an efficient market. The following methods have been used in the past to determine the prices of electricity in developing countries;

- Cost Recovery Pricing- This requires the setting of a price that allows the service provider to recover its investments costs and also gain an "acceptable" return on their investment. This can also include depreciation costs. This approach is often used in monopoly markets and in situations where the value of assets is significantly greater than the additional investments required in future periods. Determination of a fair return bounds on the investments often include both social and political objectives. It is easier to use to calculate the cost of production once a fair rate of return has been determined. One of the main disadvantages of this pricing method is that it does not provide an incentive for new firms to enter into this market. It also does not reward for efficiency and performance since the return is set based on the level of fixed assets of the utility provider and the utility provider does not have to consider cost minimization strategies given that they recover all the costs. The lack of performance based rewards and the lack of incentives for market entry leads to the disadvantages faced in a monopolized market [74].

- Marginal Cost Pricing- Prices of electricity are set equal to the marginal cost incurred by the utility to provide electricity to each additional consumer. The limitation of marginal cost pricing is that it does not take into account capital cost in the short run [64]. Energy investments are long term investments, therefore marginal costs should include the costs of expanding and capacity or improving technologies used in the generation of power.

- Opportunity Cost Pricing-The utility analyzes how much it would charge for its service if it was located in a different country. This method allows provides a good check for policy makers if the markets chosen has similar characteristics to the market under study. Since most countries do not observe the same markets conditions this methods does not provide a good check for internal pricing. For example, Zimbabwe and South Africa have some of the world largest coal reserves, but there is a huge disparity between the level of coal production in both countries. This means that using the opportunity cost pricing method with each neighbor as a reference point is not an effective pricing benchmark for either country. Country specific differences mean that the prices charged do not always reflect opportunity cost for a player in a different market [74].

- Market Pricing- This pricing method is used when there are multiple players in the market. The price converges to an optimal price for the allocation of resources in the market. Economic theory shows that this is the most efficient method of pricing. However, market pricing can induce prices that exclude access to a large number of consumers. This poses a problem for policy makers in developing countries whose objective is to provide a structure for regular and affordable electricity services to the consumers.

4.1.2 Problem Definition and Objective

The main objective of this chapter is to formulate the design of an optimal pricing path for new market players whose objective is to maximize long run profits and this has effects on the long run network size. The policy makers uses an environmental tax to control the levels of greenhouse gas emissions [125]. The market entrant faces a profit maximizing dominant incumbent whose pricing path is a profit maximization strategy. In other words, the pricing structure of the incumbent is not administered i.e. not set by a regulatory authority in line of other objectives e.g. social or political . New market players can use this optimal path model for profit maximization to inform their decisions on infrastructure investments. The model developed in this paper builds on the work of Chisari and Kessides [81], which considers a dominant utility that is facing a competitive fringe which serves customers that are not connected to the main grid. The network size of the incumbent utility depends on the price it chooses relative to the marginal cost of the competitive fringe. The work by Chisari and Kessides in turn builds off of the work by Gaskin [81]. Both assume that the incumbent utility has a cost advantage over the competitive fringe. However, Gaskin assumes that the fringe faces constant marginal costs [55] while Chisari and Kessides assume that the fringe competitor faces increasing marginal costs as the incumbent utility increases its network size [81]. Both assumptions are valid when the competitor is a small company generating and supplying electricity to customers that are not connected to the grid and does not implement control methods to maximize profit and expand its network. Gilbert criticizes this assumption that only the incumbent is presumed to act rationally , while the entrant is treated as a passive fringe that does interact strategically with the incumbent firm [56]. In our case, the entrant is an independent power supplier that is looking to provide services to customers that are connected to the grid and also expand its network to customers that are currently not receiving electricity, in order to maximize profits. Kessides and Chisari do not address this shortcoming in their model . In order to address the criticism by Gilbert, this paper models both market players as strategic players that maximizes long run profit by choosing an optimal pricing path that allows for network growth. It is assumed that the competitor and the incumbent have specific cost functions however none of the two firms has a cost advantages over the other. This is justification on the grounds that there is government effort to establish competition and move away from the use of fossil fuels. The government can insure no cost advantages by providing subsidies to new companies that face a cost disadvantage due to the high costs of entry into the market. The following table summarizes the problem we are solving compared to the ones in literature;

Table 4.1: Country Classification

Author	**Incumbent**	**Entrant**	**Limitations**
Chisari and Kessides (2009)	Π-maximization	Passive	Does not account for a serious entrant that is a profit maximizing firm
Gaskin (1976)	Π-maximization	Passive	Does not account for a serious entrant that is a profit maximizing firm
Matenga, Fedderke and Terpenny(2018)	Π-maximization	Π-maximization	

4.2 Basic Model

4.2.1 Cost Modeling

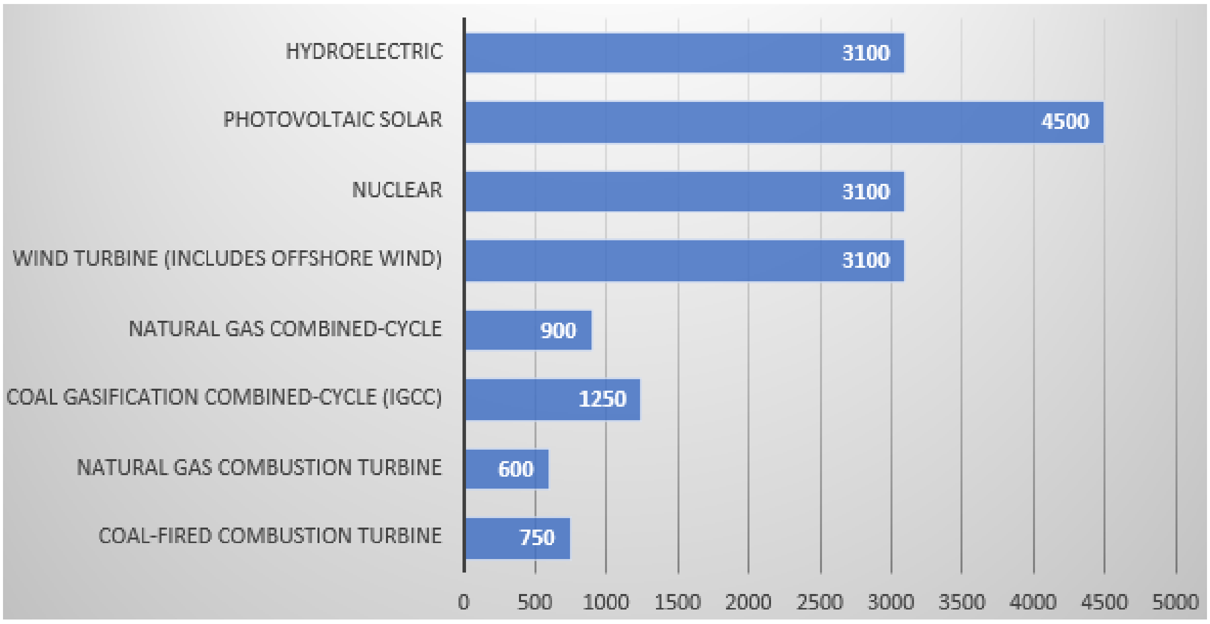
Generalized Costs

Economic dispatch(ED) problems are some of the most studied problems in power systems research. The goal of economic dispatch problems is to minimize the operational cost of power systems. The ED problem applied to power systems can be set up as a cost minimization problem. Traditional optimization techniques can be used to solve this problem. The overall cost of electricity production can be categorized into two sections; (1) Capital Costs and (2) Operational Costs [71].

Capital Costs

Capital costs are the investment expenses incurred in the setting up of the electricity generation plant. These include direct or indirect costs that are incurred by the operator before or during the plant set up process. The capital costs vary depending on the technology and size of the power plant to be installed. Often in liberalized markets, the plant with the smallest capital cost will be chosen. **Figure 4.11**, shows the capital costs range for different technologies. The data shown is from 2009, and the current trend might be slightly different from the graph shown, however it captures the relative difference in capital costs for the purposes of illustration.

Figure 4.1: **EIA Capital Cost of Power Generating Technologies($/kW)**



The conventional technologies like fossil fuels, nuclear and hydro power generating plants often require the lowest capital costs while the newer technologies like solar and fuel cells require higher capital costs. The latter technologies are still in the development stages, and the capital costs are expected to drop with time [45]. It is also important to note that while the conventional fuels have lower capital costs, they do have fuel cost functions, while the renewable sources do not have fuel cost functions. This is important in understanding the long run costs of electricity produced by each plant given their choice of technology [45]. The renewable sources do not have negative externalities on society, which is an advantage over fossil fuels.

Table 4.2: Fossil vs Renewable Fuels

Costs	**Fossil**	**Renewable**
Capital	Low	High
Marginal	High	Low = 0

Often the capital costs must be met at the beginning of the project or as soon as it is completed. Today, this might involve raising a loan that is paid over a defined period of time. The length of the period, often depends on the size and the technology of the power plant project. The length of the loan payment is usually less than 20 years, which is less than the expected lifetime of most modern power plants [45].

Operational Costs

Operational costs are the expenses that include all the cost of power generation that do not include the capital cost. These include fuel costs , maintenance, and insurance costs [71]. The capital costs can be incorporated into the cost function as fixed costs. For the purposes of cost optimization, the fixed cost will not affect the equilibrium solutions. The operational costs are generally dominated by the fuel costs [76]. Understanding the operational costs is regarded as critical since it is the most important category of the two costs mentioned above. The fuel cost function can be used to represent the operational costs of the system. A typical ED problem for N generators can be formulated as follows;

$$\min C_T = \sum_{i=1}^{N} C(P_i) \tag{1}$$

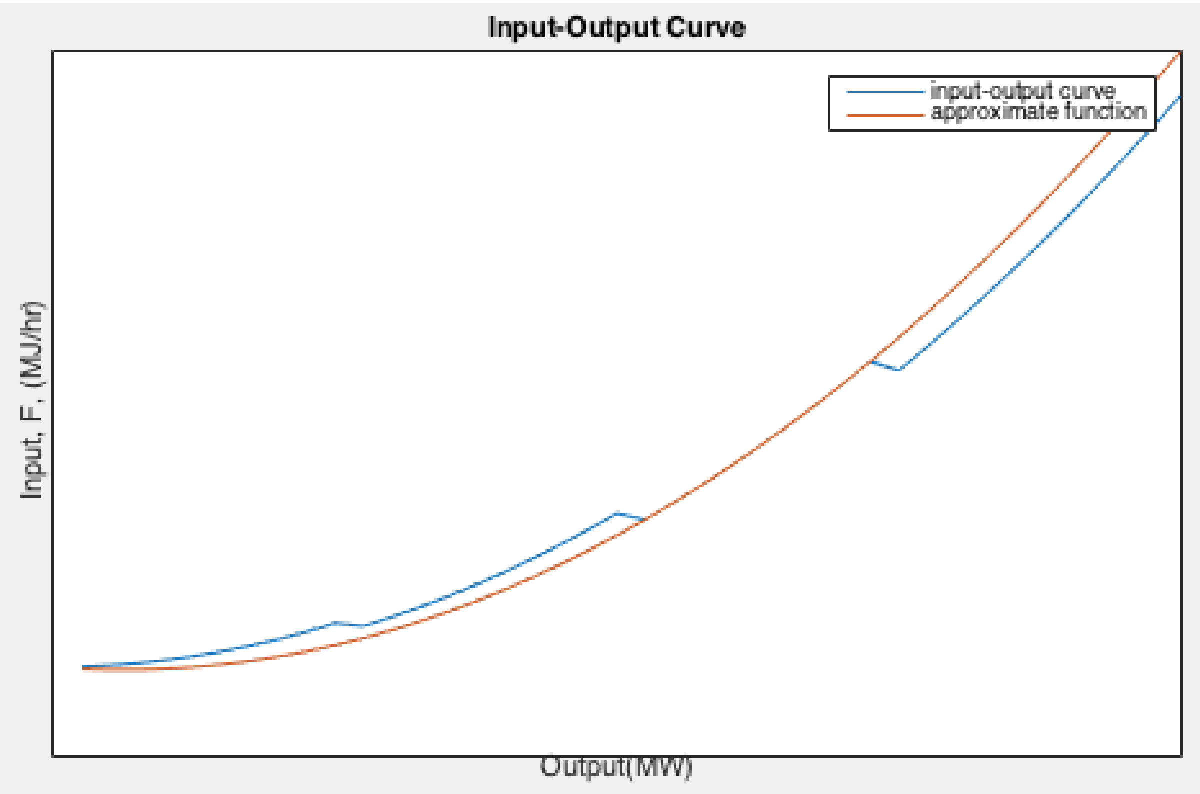
s.t

$$P_i[min] \leq P_i \leq P_i[max] \qquad i = 1, ..., N$$

Where P_i is the power output , $C(P_i)$ is the fuel cost function and C_T is the total cost. We have $P_i[min]$ as the minimum operational conditions of the generator, while $P_i[max]$ is the capacity limit of the generator [59]. It is then important to understand the functional form of $C(P_i)$. The

cost function captures the functional dependence between the electric power generated and the cost. The cost function describes the input-output characteristics of the a generator.
The input (F) in thermal power generation is measured in MJ/hr, while the units for the output (P) are given in MW (megawatts). **Figure 2**, shows a typical input -output curve. The discontinuities in the cost curves arise from a sharp increase in the throttle losses which are caused by wire drawing effects occurring at valve points [52]. According to El-Haway [52], ”These are output levels at which a new steam admission valve is being opened, and as the valve is gradually lifted, the losses decrease until the valve is completely open.” There exist multiple valves, therefore inducing high order or multiple non-linearities in the output of each generator. The input-output curve in the neighborhood of the valve points is not easily determined, therefore most utilities adopt smooth curves which can be defined by a polynomial of order , R.

Figure 4.2: **Input(F)-Output(P) curve**



A general cost curve can be represented as;

$$C(P_i) = a_0 + a_1 P_{Gi} + a_2 P_{Gi}^2 + ... + a_N P_{Gi}^R$$

$R = 2 \quad or \quad 3$ are the widely adopted orders for the cost function hence quadratic functions and cubic functions are used to model the response of conventional thermal generators when coal, gas, oil, fuel cell e.t.c are used as fuel sources. The majority of the cost function literature suggests approximating the cost function as a quadratic function under the assumption that the incremental cost curves of the thermal units are monotonically increasing piecewise linear functions [76, 52]. Thermal power plants widely use quadratic fuel cost function [76]. The following is an example of a cost function as used in [76];

$$C_i(P_{Gi}) = a + bP_{Gi} + cP_{Gi}^2 \tag{2}$$

where P_{Gi} = electrical power output , a, b, and c = fuel cost coefficients.
The cost of electricity production is quadratic in the electric power output. This models sufficiently the increase in costs of production as the power output increases. Most developing countries use energy from fossil fuels in thermal power plants, therefore this cost function is likely to be applicable in the case of developing countries. When the input-output curve cannot be approximated by a quadratic function, a function with, $R > 2$, that captures this non-linearity would be more appropriate for use in modeling costs of generating electricity in thermal plants. A more complex version of the cost function of thermal power plants is shown in [72], which often used when the quadratic function does not accurately model the input -output data. They consider a cubic cost function as follows;

$$C_i(P_i) = a + bP_i + cP_i^2 + dP_i^3 \tag{3}$$

Where P_i = electric power output,a, b, c and d = fuel cost coefficients.

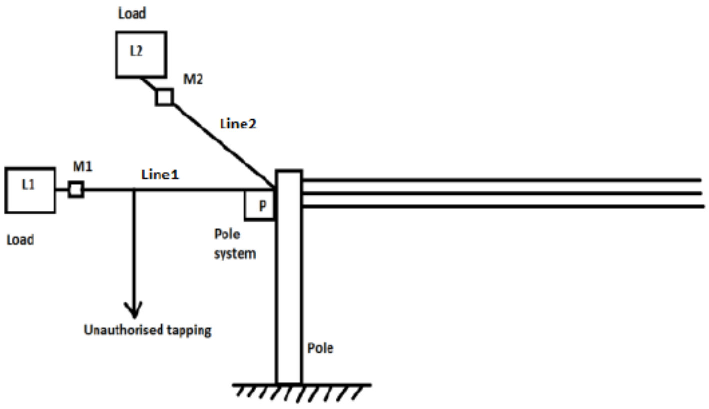
Can one accurately estimate the parameters of the cost function for a power plant? Accurately estimating the cost function parameters is important in optimizing the objective function (1). If the cost function is not a good representative of the real cost function, this renders the optimization of (1) misleading. Artificial intelligence methods like fuzzy logic and neural networks have been used to estimate the cost function parameters. Optimization methods like particle swarm optimization and genetic algorithm have also been used to accurately estimate the fuel cost curves [71, 59, 53, 69].

Electricity Theft

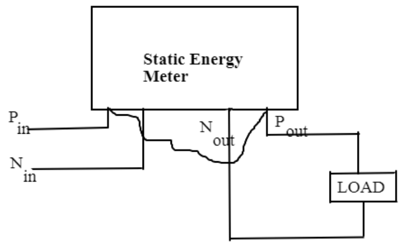
In order to maintain the balance between power generated and power demand, a utility supplier has to account for the energy lost during transmission and distribution (T&D). This loss of energy is incorporated into the cost function of the supplier. For a stable system, this loss of energy can be accounted for with high degree of accuracy. If a utility supplier cannot accurately calculate these losses, this can lead to undesirable results like black-outs. One reason that can lead to an inaccurate estimation of energy losses is not accounting for theft in the network. Joseph argues that setting the right electricity prices may not suffice in the reduction of financial instability of the utilities when there is theft in the market [61]. It is important to include all factors that contribute to energy losses, in order to meet demand in an efficient way.

Theft of electricity is defined as the use of electrical power without a contract with a supplier with total or partial bypassing of the metering system or interfering with the metering system so as to alter its measurements [70]. Total bypassing (tapping), as shown in **Figure 4.3a**, usually occurs when a formal consumer supply electricity to their unconnected neighbors. The tapping happens before the formal consumer's meter. This energy provided to the informal consumer is not accounted for in the cost charged to the formal customer. This type of theft is common in developing countries especially in high density suburbs in large cities [70]. The close proximity of the houses make it easier to connect two or more houses to one meter. This allows the families to split the bill amongst two or more families. This reduces the cost per family since the cost per month is split amongst families, this incentive outweighs the cost of being caught by the authorities. The families take advantage of the poor fraud detection methods in many developing countries. **Figure 4.3b**, shows an example of current bypass, this occurs when current is rerouted from phase input to phase output bypassing the meter in the process. Therefore the current supplied to the load cannot be measured and hence the power usage cannot be measured. The meter will not show accurate measures of power consumed.

Figure 4.3: **Illustrations of Electricity Theft**



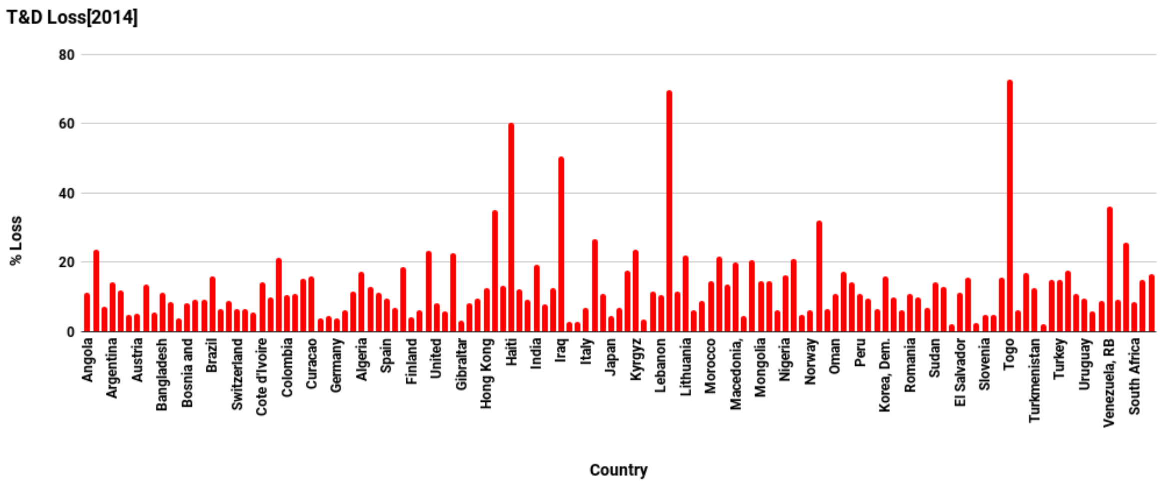
(a) Tapping



(b) Current bypass

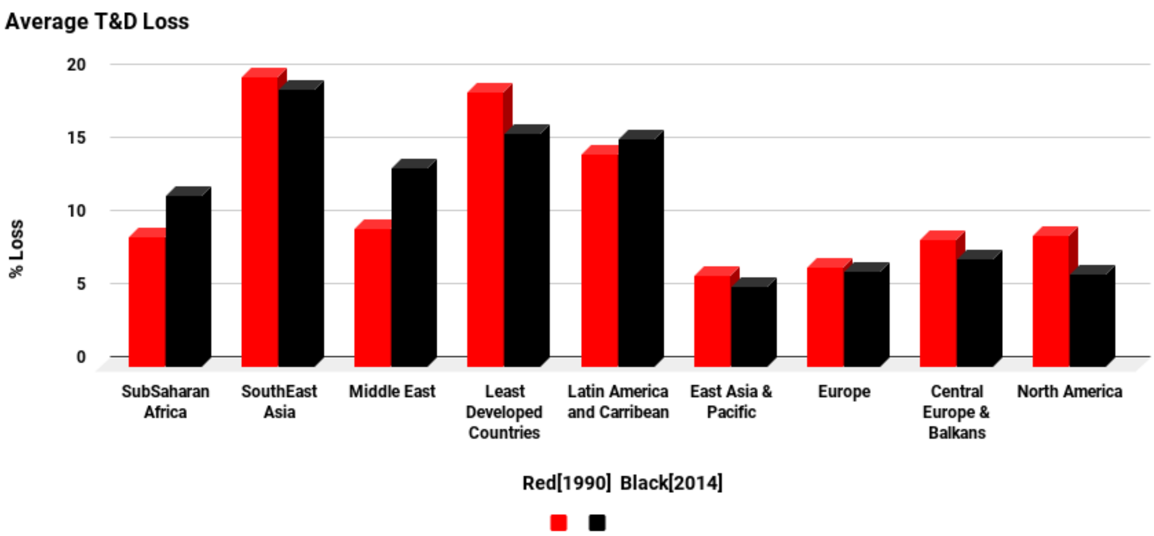
Electricity theft include billing irregularities and unpaid bills. Levels of electricity theft ranged from 0.5 % in the US to as high as 35 % in Bangladesh in 1998 [70]. The standard method of measuring electricity theft is using the analysis of the transmissions and distribution(T&D) losses. T&D measures the difference between the amount of electricity generated into the grid and the amount that is sold to the consumers. When an accurate calculation of (T&D) is made, theft may contribute significantly to the unaccounted losses [70]. Using the data from the World Bank's Development Indicators (2017), we can show the levels of T&D losses for individual countries in 1990 and 2014. Figure 4, shows a graphical representation of the losses for a range of countries in 2014. The developing countries incur higher losses compared to the developed countries. Some places like Togo face as high as 72% losses.

Figure 4.4: **T& D Losses**



While the country comparison is important, the regional comparison of changes in T&D losses is also valuable in assessing the regions that are mostly affected by large T&D losses. Figure 5, shows T&D losses of each region in 1990 and 2014.

Figure 4.5: **Average T& D Losses by Region**



The graph shows that regions like Europe , North America and East Asia have seen a decline in T&D losses over time, while regions like Sub Saharan Africa, South East Asia, Middle East and Latin America have seen an increase in the average T&D losses. These are also the regions that have the greatest number of least developed countries compared to other regions that have seen a decline in T&D losses. The Middle East has seen a number of military conflicts between 1990 and 2014 , and this might be a reason for the increase in T&D losses since war can compromise the infrastructure of the hosting country.

In the literature power systems with $16 \leq \%(T\&D) \leq 40\%$, have been viewed as systems with extensive theft, while $(T\&D) \geq 40$, are systems with serious problems [70]. Due to significant improvements in technology we expect a reduction in (T&D)losses. Therefore the definition of extensive theft and severe theft as used in [70] is not applicable in today's conditions. Instead, we can redefine the (T&D) ranges as ; $10 \leq \%(T\&D) \leq 20\%$, are systems with extensive theft, while $(T\&D) \geq 20$, for systems with severe theft problems. We define levels of theft severity as; $0, 1, 2$ where $0(normal)$ =$\%(T\&D) \leq 10$, $1(extensive)$ = $10 \leq \%(T\&D) \leq 20\%$ and $2(severe)$ ≤ 20. Using the data from the World Bank's Development Indicators(2017), we obtain **Table 1** and **Table 2** as in [70].

Table 4.3: Country Classification

T/D Loss(%)	**Number of Countries**	**Overall %**
0-10 (normal)	59	45.04
10 -20(extensive)	53	40.46
$\geq$ 20 (severe)	19	14.50
Total	131	100

Table 4.4: Geographical and Economical Region Statistics

Region	Average	Standard Deviation	% Change [TD(2014)-TD(1990)]	Severity
Sub-Saharan Africa	10.84	0.99	2.83	1
South-East Asia	21.60	3.05	-0.82	1
Middle East	11.47	1.58	4.20	1
Least Developed Countries	15.67	1.51	-2.81	1
Latin-America and Caribbean	15.58	0.54	1.03	1
East-Asia & Pacific	6.13	0.32	-0.74	0
Europe	6.77	0.32	-0.36	0
Central-Europe & Balkans	9.69	1.55	-1.26	0
North-America	6.52	0.74	-2.68	0

Source = World Bank 2017

Table 4.3, shows that 55% of the world countries face extensive to serious levels of electricity theft. The majority of these countries are drawn from the developing countries. **Table 4.4**, grouped the countries by geographical and economic regions. When the countries are grouped by region; Sub Saharan Africa, South East Asia, Middle East and Latin America and Caribbean regions experience the most technical and distribution losses. Most developing countries fall into these regions. The most developed regions like North America, East Asia and Europe have low levels of T&D losses. Most of the regions recorded a decrease in T&D losses between 1990 and 2014, these were attributable to improvements in technology. The impact of theft is felt by the utilities in terms of financial losses , the need to increase tariffs to formal consumers and the increased costs of maintaining grid stability. The NorthEast energy consulting group report showed that utilities lose approximately $ 96 billion dollars per year to non-technical losses and electricity theft contributes significantly to these losses [65]. It notes that these losses are crippling to both the consumers and the utilities as they result in price hikes to formal customers, financially unsustainable markets and reduce the resources for future capital investments. Evidence show that countries with political instability, high levels of corruption, low government effectiveness and low effective accountability face high levels of theft [70]. Most developing countries if not all, face some or all of the conditions that encourage high levels of theft. While there are proven remedies for theft like tamper-proof meters, regular monitoring and inspection, they still lag behind in implementation of these methods compared to the developed world. It is important for utilities in these countries to consider the effects of theft for optimal operations in these countries.

Public Utility Operational Costs

The cost functions (2) and (3) only model the cost incurred from production, and do not model the additional cost incurred by the utility due to electricity theft. An appropriate model that incorporates both the cost due to generation and theft is required for modeling developing countries generation costs. The cost incurred due to theft is especially important to a state owned utility (incumbent) that maintains the grid. An accurate understanding of the cost structure enable the utility to make optimal decisions. In order to maintain the grid load the incumbent is forced to produce more electric energy in the presence of theft to maintain grid stability than it would to meet its formal demand. We define grid stability as the maintenance of a balance between supply and demand of electricity. Grid instability can lead to blackouts. While there are other causes of blackouts like weather, power plant failure e.t.c, our focus is on the blackouts that are caused by demand exceeding supply. Blackouts cause both social and economic costs [10]. The dependence of productivity and social welfare on the access of regular and uninterrupted electricity supply is well established. Both factors contribute to economic development, therefore uninterrupted electricity supply is important for economic growth. A number of studies have estimated the social and economic costs of black out. Different models have been developed to accurately estimate these losses [54, 43]. A government in a developing country may seek to minimize these losses by regulating that the incumbent must maintain grid stability. Since the state has social, economic and political reasons to ensure grid stability, therefore the incumbent utility is required by law to guarantee grid stability. The state can argue that the lack in supply is not a result of lack of energy sources but the choice of the incumbent to not meet demand. This is especially true in developing countries where state owned monopoly often purchase fossil fuels at prices lower than the market value. By making a statutory requirement, the incumbent utility is forced into maintaining grid stability. In addition, it can be the case that the incumbent utility losses due to blackouts are higher than the costs of maintaining grid stability.

Chisari and Kessides considered an incumbent utility that is required to maintain grid stability. This means that any theft that occurs, has to be modeled into the cost function of the utility. Including theft in the cost function model is consistent with the argument in [61] on the importance of including cost due to theft in the optimization problem. They adopted a cost function for the incumbent that considers the cost incurred by the incumbent due to theft. Since tapping is more rampant compared to other forms of theft, their model only considers the costs due to tapping. They adopt a convex cost function in the size of the network, N. Let, N, be the number of customers that are formally connected to the network. This implies that as the network size increases, the cost incurred by the utility provider increases since the amount of fuel needed to meet demand is directly proportional to the network size. They use N as a proxy of the amount of electricity produced. This assumption is valid for an incumbent that maintains grid stability. They consider a market with ,M potential consumers and the incumbent is currently serving a network size N. The remaining $M-N$ consumers either have no access, or a certain ρ of them are stealing service from the grid through illegal connections. The following is the cost function of the incumbent that is convex in N ;

$$C^{\rho}(N) = F + aN + c[\rho M + (1-\rho)N]^2, \qquad a > 0, \qquad c > 0. \tag{4}$$

Where ρ is the percentage of customers stealing services from the utility,
We can show that this cost function (4) has the same functional form as (2) and that it is only convex in the size of the network, N. The following paragraphs explain why equation (4) captures the cost function of an electricity producer in a developing country.
We assume that theft only occurs when there is a difference between the market size (M) and the network size (N), since they only considered theft due to tapping, thus $M > N$ for $\rho \in [0,1)$. Let C^{ρ} be the cost function for any $\rho \in [0,1]$. Since C^{ρ} is the cost function for any $\rho \in (0,1)$, then we have $C^1 > C^{\rho} > C^0$. Therefore, $C^{\rho} \in [C^0, C^1]$, in other words, as ρ increases , the cost incurred by the incumbent increases. We can also expand (4) to illustrate how it captures the cost incurred by the incumbent. The following is the expanded version of (4);

$$C^{\rho}(N) = F + aN + 2c\rho(1-\rho)MN + c(1-\rho)^2N^2 + c\rho^2M^2 \tag{5}$$

If we substitute for the extreme cases of ρ we arrive at C^1 and C^0 as (9) and (11).However this formulation does not explain the interaction term MN. In (5), the interpretation is that as M and N increases, the cost incurred by the utility provider increases. However, for a given market, M is fixed, therefore M is part of the coefficient $2c\rho(1-\rho)M$ of N, which is a variable. In order to understand this term, re-write (4);

$$C^{\rho}(N) = F + aN + c[N + \rho(M-N)]^2 \tag{6}$$

We can then expand (6) to get the following;

$$C^{\rho}(N) = F + aN + c[N^2 + 2\rho(M-N)N + \rho^2(M-N)^2] \tag{7}$$

The cost function is convex in both N and $M-N$ as shown by equation (7). It should be noted that at any given point in time , M is fixed. The cost function increases as $[M-N]$ shrinks, however the rate of increase is less than the rate of increase of the cost function when $\rho = 0$.

Lemma 2 *The rate of increase of the cost function when $\rho \in (0,1)$ is less than the rate of increase of the cost function when $\rho = 0$ i.e $\frac{dC^{\rho}}{dN} < \frac{dC^{0}}{dN}$.*

Proof. We show this by proving that $\frac{d^2C^{\rho}}{dN^2} < \frac{d^2C^{0}}{dN^2}$, since each second order derivative measures the rate of change of the first derivatives i.e $\frac{dC^{\rho}}{dN}$ and $\frac{dC^{0}}{dN}$. We can take the second derivatives of C^{ρ} w.r.t N for $\rho = 0$ and $\rho \in (0,1)$;

$$\frac{d^2C^0}{dN^2} = 2c$$

and

$$\frac{d^2C^{\rho}}{dN^2} = 2c(1-\rho)$$

Since $\rho \in (0,1)$, we have $\frac{d^2C^{\rho}}{dN^2} < \frac{d^2C^{0}}{dN^2}$ which implies that $\frac{dC^{\rho}}{dN} < \frac{dC^{0}}{dN}$ ■ Intuitively, C^{ρ} already accounts for the costs incurred for supplying some of the informal network, therefore if N increases, the incumbent already accounted for the cost of part of the change in N. This is not the case when $\rho = 0$. For completeness, we note that $\frac{dC^{\rho}}{dN} = 0$ when $\rho = 1$. Thus , $\frac{dC^{0}}{dN} > \frac{dC^{\rho}}{dN} > \frac{dC^{1}}{dN}$.

Lemma 3 *(4) is only convex in N iff M is a constant i.e it has the same functional form as (2)*

Proof. Re-arrange(7) as follows;

$$C(N) = [F + c\rho^2M^2] + [a + 2c\rho(1-\rho)M]N + c(1-\rho)^2N^2$$

Let $\mathbf{F} = [F + c\rho^2M^2]$, $\mathbf{a} = [a + 2c\rho(1-\rho)M]$ and $\mathbf{c} = c(1-\rho)^2$, therefore;

$$C(N) = \mathbf{F} + \mathbf{a}N + \mathbf{c}N^2 \tag{8}$$

■ This is consistent with the fuel cost function (2) which is convex in the amount of electricity power produced. It also increases as ρ increases, as explained above.

Lets take the extreme conditions where $\rho = 1$ and $\rho = 0$. When $\rho = 1$, there exist perfect stealing and the whole population ,M , has access to the utility services. Thus;

$$C^1(N) = F + aN + cM^2 \tag{9}$$

Lemma 4 *Equation (9) does not underestimate the cost incurred by the incumbent utility iff* $N = M$.

Proof. In the absence of theft, if there is perfect access to electricity i.e. 100% coverage then the cost function(C^m) is equivalent to;

$$C^m(N) = F + aM + cM^2 \tag{10}$$

If $N < M$,then $(10) - (9) = a(M - N) > 0$, thus (9) will underestimate the true cost incurred by the incumbent if we use the value of $N < M$. We know that N is bounded above by M therefore $N \leq M$. In order to not underestimate the cost incurred, we adopt (10) when $\rho = 1$. ■
Underestimating the cost function, implies underestimating the energy required to meet market demand. This can lead to blackouts, and the effects of blackouts have already been discussed in earlier paragraphs. Also, C^1 becomes deterministic and a constant for a given market.
When $\rho = 0$, it means there is no service theft i.e the cost incurred by the utility are for servicing its current network. Let C^0 be the new cost function for the utility provider;

$$C^0(N) = F + aN + cN^2 \tag{11}$$

Equation(11) is convex in N, which is consistent with the original formulation (4) which is a convex function like (2), which is a general convex function in the amount of power produced.

Externalities

One of the resultants of fossil fuel electricity generation is pollution. This is especially true in thermal power plants that use fossil fuels. The burning of fossils fuels emits pollutants such as $S0_2$, CO_2, $N0_x$. These gases lead to acid rain and and cause different ailments. Holland et al showed that air pollution has negative effects on health and contributes to mortality rate, cardiovascular and respiratory illness [60]. He quantified the impacts of coal operated power plants in South Africa to be valued at $ 2.4 billion annually. This is approximately 20 % of the valued annual damage in the OECD circle study. The cost of the impacts caused by the coal fired plants accumulates yearly during the lifetime of the plant. With average lifetimes of nearly 20 years for thermal power plants, the costs on the the population becomes very large [60]. In recent years there has been a push amongst nations to gradually transition to greener energy sources as the consequences of climate change have become more apparent. According to the World Bank environmental indicators, the world combined released 4.972 metric tons per capita in 2014. With the exception of South Africa, African countries emit less $C0_2$ for a unit of GDP than the world average. This is a result of the lower levels of industrialization in developing countries and lower levels of electricity access. The level of $C0_2$ emissions is directly proportional to the levels of electricity demand. Therefore the lower levels of demand in developing and African countries explain the low $C0_2$ emissions per capita. Both academics and policy makers are concerned about the best way to reduce greenhouse effects and minimize the economic effects that can arise from such action.

Tradable Permits vs Emission Taxes

On December 10, 1997, 160 countries signed the Kyoto Protocol agreement on limiting emissions of greenhouse gases. This set in motion the debate on how to efficiently achieve the reduction in pollution in different economies. Economic literature draws a clear distinction between command and control approaches (CAC) and market-based incentives (MBI), with the latter being preferred over the former [125]. Two MBI instruments have been used as a control strategy for green house emission reduction: Enviromental taxes and tradable permits have been adopted by different countries over the past two decades. The main challenge to policy makers is knowing which instrument to adopt and under what conditions it will be most efficient. There is established economic literature that details the efficient conditions to implement either the environmental tax or the tradable permits.

Environmental Taxes

Environmental taxes are known as Pigouvian taxes. This is a tax that is charged on any market activity that impose costs on the society (negative externalities). The intent of this tax is to move the market from an inefficient point to an efficient point where the cost to society is lower than the inefficient point. In energy economics, this can be achieved by levying a carbon tax on power suppliers. The tax levied on the suppliers needs to be equal to the total damage caused by the extra unit of emissions. This means that the tax needs to be a true reflection of the cost to society, therefore the power supplier has an incentive to reduce emissions until a unit reduction in emission is equal to the social damage [60]. According to Van Heerden, the Pigouvian tax has four effects on an economy [58];

1. They result in an increase in production costs in energy intensive industries. Thus, reducing export demands of energy intensive goods , making imports a more attractive alternative. This reduces the output in energy intensive trade related sectors. There is also a shift in labor supply from energy intensive sectors to less energy intensive sectors.

2. They increase revenue collected by the government; however, this revenue needs to be distributed in order to avoid a reduction in purchasing power. Thus resulting in a decrease household consumption.

3. They cause a decrease in GDP because the tax causes an increase in prices thereby increasing inflation. The unskilled worker wage rate is proportional to the CPI increases as inflation rises thereby reducing unskilled labor in the workforce.

4. They cause substitution form energy and energy rich commodities to sectors with low energy consumptions. This reduces demand in energy, therefore resulting in a decrease in greenhouse gas emissions.

Tradable permits

Tradable permit system requires the regulator to investigate and set a cap on the levels of pollution allowed for a specific industry. In this case it is the levels of pollution allowed for electricity generation. Once the pollution cap is established, the regulator issues permits that amounts to the cap limit e.g. a cap of 3 000 000 tonnes of $C0_2$ will require 3 000 000 permits. These permits are either distributed to the participating firms or a sold in a blind auction (highest bidder wins). No firm is allowed to emit pollution without acquiring the equivalent number of permits. After acquiring the permits, a firm can buy or sell permits to/from other firms. Tradable permits can induce innovation and development as firms seek ways to minimize costs. A potential shortfall of tradable permits is in dealing with market power. Koustaal and Xepapadeas separately established that firms when firms behave as price setters , the gains of tradable permits are lost [62, 75]. The following table summarizes the main finding of the discussion in [125];

Table 4.5: Summary of Efficiency Considerations and Market Structure

Market Structure	**Emission Tax**	**Tradable Permits**
Perfect Competition	Efficient	Efficient
Noncompetitive market in the output market	Efficient can be achieved by suitably adjusting the Pigouvian tax but only if firms are all identical	Inefficient but literature suggests that efficiency losses may be smaller than under an emission tax(when firms have different pollution technologies).
Noncompetitive market structure in the permits market	N.A	Inefficient

Source = Norregaard and Repellin-Hill 2000

The importance of privatization is supported by the inefficient levels that are achieved by both the emissions tax and tradable permits in a monopolistic market [47]. By introducing competition, the market becomes efficient under both the emission tax or the tradable permits. It is important to note that the environmental tax achieves social optimum [68] when the firms causing pollution are identical i.e they use similar technology for electricity production. In the case of dissimilar technologies, only the firm specific environmental tax achieves the social optimum [68]. We model the emission tax as part of the cost to the utility. Therefore we extend the cost function by Chisari and Kessides to include the cost of emission tax. We assume that the marginal cost of emission increase as the production capacity increases. Let, ν_i be the emission tax imposed on the utility. Therefore the new cost function is;

$$C^{\rho}(N) = F + aN + c[\rho M + (1-\rho)N]^2 + \nu N^2, \quad a > 0, \quad c > 0 \quad \nu > 0. \tag{12}$$

Entrant Firm Operational Costs

For the case of the entrant firm; the entrant does not own the grid network, but it can directly bill its own consumers. Unlike the incumbent that considers theft as a cost. The entrant does not carry the burden of maintaining grid stability i.e it only incurs costs of supplying electricity to its own network. Therefore it does not consider costs due to theft. This is a clear distinction between the incumbent and the entrant utility. The cost function for the entrant is equivalent to the cost function of the incumbent supplier when $\rho = 0$. Any theft that occurs for the entrant will be considered as revenue that is not realized. This will be true in the presence of current bypass theft as illustrated in **Figure 3b**. If the entrant firm does not directly collect revenue from the customers, it can receive its revenue from a third part namely a local municipal or the government. This can lead to to the entrant not receiving all the revenue it should be receiving from its consumers. Let, a fraction τ of the revenue owed to the supplier by the government is not paid to the utility. This is called unrealizable revenue. This is common in markets with poor government systems. We also include the adjustment costs as part of the cost function. An entrant utility that adopts the conventional fuels for energy production uses the quadratic cost function to model the costs incurred for its optimization problem. The entrant firm also faces an environmental tax ν for greenhouse emissions. We define the cost function of the entrant firm as follows;

$$C(N_e) = F + aN_e + cN_e^2 + \phi \dot{N_e}^2 + \nu_e N_e^2, \quad a_e > 0, \quad c_e > 0 \quad \nu_e > 0. \tag{13}$$

Where, $F \geq 0$ are the fixed costs for each utility provider, $\phi \dot{N}^2$ is the adjustment cost in network size, ν is the emissions tax.
The cost function of the entrant (12) is equivalent to (11), for the incumbent, when $\rho = 0$.

If $\tau > 0$, we represent the unrealized revenue in the profit function of the entrant. Therefore, the general profit function of the entrant utility using the cost function described above is as follows;

$$\Pi_e = (1-\tau)P_eN_e - [F + aN_e + cN_e^2 + \phi\dot{N_e}^2] \tag{14}$$

Where τ is the percentage of customers using current bypassing methods.
This is the profit function that we use in the profit maximization problem for the entrant firm.

4.2.2 State Dynamics

Incumbent Utility

The state dynamics captures the change of the state variable with time. In our model, the state variable is the network size, N. We define the rate of change of the network size as follows;

$$\dot{N_d} = \alpha_D[\beta_eP_e(t) - \beta_dP_d(t)] \tag{15}$$

Where ,
N_d is the network size of the incumbent firm.
β_e is the price responsiveness of the entrant consumers
β_d is the price responsiveness of the incumbent consumers
α_D is the market potential for the incumbent firm

From equation 1, we note that the rate of change of network size is proportional to the market potential, $\alpha_D(t)$, of the incumbent firm. For the purpose of the analysis in this paper, we assume $\alpha_D > 0$, to capture the under-coverage that already exist in developing countries. Therefore,the larger , α_D ,the larger the potential for growth for the firm. Each utility can only increase its network by adding consumers that it does not currently serve. The rate of change also depends on the prices that are being charged by each firm , as the price charged by the incumbent increases the rate of change of the network size decreases.

The rate of change of network size only depends on the price elasticity responsiveness of the consumers (β) for each firm's electricity and the price level set by the firm . Each utility gains extra revenue by implementing lower prices. Also, $\beta_e \gtreqless \beta_d$, i.e when the $\beta's$ are equal, the network growth depends purely on the price differential between the two firms. It might also be the case that,$\beta_e > \beta_d$, i.e. consumers are more responsive to the price level set by the entrant firm. This might be due to the good reputation that the incumbent have in the market or the reluctance of customers to go through the process of changing service providers. In the case where the incumbent has a poor reputation due to poor service delivery;$\beta_e < \beta_d$, as consumers shift from the monopoly to the entrant firm. We rewrite $\beta's$ as a function of each other. Thus;

$$\beta_e = \eta_d\beta_d \qquad \eta_d \gtreqless 1 \tag{16}$$

Therefore equation(15) can be written as ;

$$\dot{N}_d = \beta_d \alpha_D [\eta_d P_e - P_d] \tag{17}$$

From (15), $\dot{N}_d > 0$ when $\eta_d P_e > P_d$ which means $\frac{P_e}{P_d} > \frac{1}{\eta_d}$. This is a necessary and sufficient condition. We analyze three possible condition, (a)$\beta_e = \beta_d$ (b) $\beta_e > \beta_d$ and (c) $\beta_e < \beta_d$. The proofs of these scenarios are shown in the appendix.

Entrant Utility

By following the same analysis as above, we can formulate the state dynamic equation of the entrant firm as follows;

$$\dot{N}_e = \alpha_E [\beta_d P_d - \beta_e P_e] \tag{18}$$

Where ,
α_E is the market potential for the entrant firm
N_e is the network size of the entrant firm.
β_e is the responsiveness of the consumers to the entrant price
β_d is the responsiveness of the consumers to the incumbent price

From equation(2), the rate of change of the network size of the entrant is proportional to the market potential $M - N_e > 0$. When the $\beta's$ are equal, the network growth depends on the price differential between the two firms. From (2), $\dot{N}_e > 0$ when $\beta_d P_d > \beta_e P_e$ which means $\frac{P_d}{P_e} > \frac{\beta_e}{\beta_d}$. We have, $P_d > P_e$, when $\beta_e = \beta_d$, intuitively customers would prefer joining a network where the prices are lower. We rewrite $\beta's$ as a function of each other. Thus;

$$\beta_d = \eta_e \beta_e \qquad \eta_e \gtreqless 1 \tag{19}$$

Therefore equation(1) can be written as;

$$\dot{N}_e = \beta_e \alpha_E [\eta_e P_d - P_e] \tag{20}$$

From (5), $\dot{N}_e > 0$ when $\eta_e P_d > P_e$ which means $\frac{P_d}{P_e} > \frac{1}{\eta_e}$. This is a necessary and sufficient condition. We analyze three possible condition, (a)$\beta_e = \beta_d$ (b) $\beta_e > \beta_d$ and (c) $\beta_e < \beta_d$. The proofs of these conditions are similar to the ones shown for the incumbent.

Results and Analysis

4.3 Nash Equilibrium

From the set up above, there are two players that are interacting strategically. These are the incumbent utility and the entrant utility. Each player choses a price,P, which is the control variable for the maximization problem for each utility for each time period. Each utility has information about the cost structure of the other player; however, the players might not know the parameter values of the cost function of the other player. The players move simultaneously, i.e each players make decisions without observing the decision of the other player. Therefore, each players anticipates that its competitor will make the best strategy, which leads to an iterative best response to the best response for each player till the end of the time horizon.

4.3.1 Incumbent Firm

Reflecting on the previous discussions and noting that the utility incurs a cost to adjust its network size. Let the adjustment cost be , $\phi\dot{N}^2$, which shows increasing adjustments cost as the change in network size increases. Let the cost function for the incumbent utility be defined as;

$$C_d(N_d) = F_d + a_d N_d + c_d[\rho M + (1-\rho)N_d + (1-\rho)N_e]^2 + \nu {N_d}^2 + \phi {\dot{N_d}}^2 \quad a_d > 0, \quad c_d > 0 \quad \nu > 0, \quad F_d \geq 0 \tag{21}$$

Where F_d are the fixed costs for each utility provider, $\phi\dot{N}^2$ is the adjustment cost in network size [46, 57], ν is the emissions tax and c_d are the marginal costs.

In order to get the Nash Equilibrium, we maximize the profit function of each utility. We start by solving the optimal control problem for the incumbent.

The total revenue received by the utility is, $P_d N_d$, therefore the utility's long run profit maximization problem is defined as follows;

$$\max_{P_d(t)} \Pi_d(t) = \int_0^{\infty} e^{-r_d t}[P_d N_d - C_d(N)]dt \tag{4.1}$$

subject to
(a) $\dot{N_d} = \alpha_D \beta_d[\frac{1}{\eta}P_e - P_d]$
(b) $N_d(0) = Nd_0, given$
(c) $N = N_d + N_e$
(d) $lim_{t\to\infty}[N_d(t)e^{-r_d t}] = 0$. (**Transversality Condition**)
Where α_D is the market potential and β_d is the price elasticity of demand.

The constraint (a) represent the change in the network size due to the price differential, (b) represents the initial network size of the the utility while (c) is the number of consumers served by both utility firms.

Transversality Conditions

The problem defined in this paper is an infinite horizon optimization problem. Since this is a discounted problem, it is easy to see that as, $t \to \infty$, the objective function $\Pi_d(P_d(t), N_d(t), T) \to 0$. We know that the state variable $N_d(t)$ is bounded by M, the size of the market. We use the results on transversality obtained by Chiang [48]. The first order conditions of maximizing the objective function with a small perturbation is defined as follows;

$$\frac{\partial \Pi_d}{\partial \varepsilon} = e^{-r_d t}[\int_0^{\infty}[(\frac{\partial H}{\partial N_d} + \dot{\lambda}_d)q(t) + \frac{\partial H}{\partial P_d}p(t)]dt + \lim_{t\to\infty}[H]_{t=T}\Delta T - \lim_{t\to\infty}\lambda_d(t)\Delta N_T] = 0 \quad (23)$$

Where N_d is the state variable,P_d is the control, H is the Hamiltonian, p(t) and q(t) are the perturbing curves for P and N. In order to satisfy the first order condition all the three distinct terms above have to equal zero. Let; $A = \int_0^{\infty}[(\frac{\partial H}{\partial N_d} + \dot{\lambda}_d)q(t) + \frac{\partial H}{\partial P_d}p(t)]dt$
$B = \lim_{t\to\infty}[H]_{t=T}\Delta T$
$C = \lim_{t\to\infty}\lambda(t)\Delta N_T$
Only B and C give rise to transversality conditions.
Since time is not fixed, we know that $\Delta T > 0$. Therefore, one transversality condition that makes $B = 0$ is ;

$$\lim_{t\to\infty}[H]_{t=T} = 0$$

It is known that $N_d(t)$ is bounded by M. This implies that $\Delta N_T = 0$. This condition is sufficient to make $C = 0$ without imposing any restrictions on $\lambda_d(T)$. We have $\lim_{t\to\infty} N_T = N_\infty$. For the discounted optimization problem, we have ;
$\lim_{t\to\infty} N_d e^{-r_d t} = e^{-r_d t} N_\infty$
We can rewrite this condition as follows;

$$\lim_{t\to\infty} N_d e^{-r_d t} = 0$$

This is the transversality condition we will use in this paper. The same conditions hold for the entrant firm.

Let the Hamiltonian be defined as;

$$H_d(N_d, P_d, T, \lambda_d) = e^{-r_i t}\Pi(P_d, N) + \lambda_d \dot{N}_d$$

Where λ_d = costate variable or the shadow price.

$$H_d(N_d, P_d, T, \lambda_d) = e^{-r_i t}[P_d N_d - C_d(N_d)] + \lambda_d \alpha_D \beta_d [\frac{1}{\eta} P_e - P_d]$$

From the Hamiltonian we have the following first order conditions necessary for intertemporal maximization problem [67];

$$\frac{\partial H_d}{\partial P_d} = H_{dP_d} = e^{-r_d t}(N_d + 2\phi \beta_d^2 \alpha_D^2 [\frac{1}{\eta} P_e - P_d]) - \lambda_d \alpha_D \beta_d = 0 \quad (24)$$

$$\frac{\partial H_d}{\partial N_d} = H_{dN_d} = e^{-r_d t}(P_d - \dot{C}_d(N_d)) = -\lambda_d' \quad (25)$$

Lemma 5 *The first-order conditions (24) and (25) are sufficient for optimum conditions iff* $2\phi \beta_d^2 \alpha_D^2 \ddot{C}(N_i) - 1 > 0$.

Proof. The *Mangasarian Sufficiency Theorem* [63], states that the necessary conditions of the *Maximum Principle* are also sufficient for the global maximization of the objective function if the Hessian matrix of H_i, denoted by $\hat{H}_i$, is negative definite, i.e.

$$\hat{H}_d = \begin{bmatrix} H_{N_d N_d} & H_{N_d P_d} \\ H_{P_d N_d} & H_{P_d P_d} \end{bmatrix} < 0$$

From (3) and (4) we have the following ;

$$H_{N_d N_d} = -e^{-r_d t} \ddot{C}(N_d)$$

$$H_{N_d P_d} = H_{P_d N_d} = e^{-r_d t}$$

$$H_{P_d P_d} = -2\phi \beta_d^2 \alpha_D^2 e^{-r_d t}$$

Therefore,

$$H_{N_d N_d} H_{P_d P_d} - H_{P_d N_d}^2 = e^{-2r_d t}[2\phi \beta_d^2 \alpha_D^2 \ddot{C}(N_d) - 1]. \quad (26)$$

Since $\ddot{C}(N_d) > 0$ by construction then $H_{N_d N_d} < 0$, if $2\phi \beta_d^2 \alpha_D^2 \ddot{C}(N_d) - 1 > 0$ then $\hat{H}_d$ is negative definite. That means the Hamiltonian H_d is concave in (N_d, P_d) and the *Mangasarian Sufficiency Conditions* are met. ■ Similar to [81], we define the current value Hamiltonian and it is maximized with respect to P_d. The following is the Hamiltonian equation;

$$H^c = \Pi(P_d, N_d) + \lambda_c \beta_d \alpha_D [\frac{1}{\eta} P_e - P_d]$$

where λ_c is the current value Langrage multiplier.

Lemma 6 *The first order condition of H^c at the optimum is given by;*

$$\frac{\partial \Pi(P_d, N_d)}{\partial P_d} - \frac{\beta_d}{r_d}\frac{\partial \Pi}{\partial N_d} = 0 \tag{27 a}$$

Proof. First define λ_c as;

$$\lambda_c = \lambda e^{r_d t} \tag{27 b}$$

Rearanging (b) we have ;

$$\lambda = \lambda_c e^{-r_d t}$$

Take the derivative with respect to t ;

$$e^{r_d t}\lambda' = \lambda_c' - r_d\lambda_c \tag{c}$$

From the definition

$$H^c = e^{rt}H$$

Thus;

$$H_{N_d}{}^c = e^{r_d t}(H_{N_d}) = -e^{r_d t}\lambda_c'$$

From H^c;

$$H_{N_d}{}^c = \frac{\partial \Pi}{\partial N_d} = r_d\lambda_c - \lambda_c'$$

make λ_c the subject ;

$$\lambda_c = [\lambda_c' + \frac{\partial \Pi(P,N)}{\partial N_d}]\frac{1}{r_d}$$

we also have;

$$H_P{}^c = \frac{\partial \Pi}{\partial P_d} - \lambda_c\beta_d\alpha_D = 0 \tag{27 c}$$

sub λ_c into $H_P{}^c$ to get,

$$\frac{\partial \Pi(P,N)}{\partial P_d} - [\lambda_c' + \frac{\partial \Pi(P,N)}{\partial N_d}]\frac{\beta_d\alpha_D}{r_d} = 0$$

$$\frac{\partial \Pi(P,N)}{\partial P_d} - \frac{\lambda_c'\beta_d}{r_d} - \frac{\partial \Pi(P,N)}{\partial N_d}\frac{\beta_d\alpha_D}{r_d} = 0$$

At the optimum, λ_c is a constant, therefore, $\lambda_c' = 0$, thus;

$$\frac{\partial \Pi(P,N)}{\partial P_d} = \frac{\partial \Pi(P,N)}{\partial N_d}\frac{\beta_d\alpha_D}{r_d}$$

■

From (27a), the first term , $\frac{\partial \Pi(P,N)}{\partial P_d}$, measures the marginal increase in the current profit for the incumbent firm due to an increase in the price it set. While the second term, $\frac{\partial \Pi(P,N)}{\partial N_d}\frac{\beta_d\alpha_D}{r_d}$, measures the marginal decrease in future profits due to the change in the decrease in the network size of the utility induced by the increase in price. The change in network size is proportional to $\frac{\beta_d \alpha_D}{r_d}$. An increase in P_d, changes the price ratio $\frac{P_d}{P_e}$, or in other words, it reduces the price differential between the incumbent and the entrant firm. This can lead to a loss of consumers to the entrant firm and reduces the expansion rate of the firm. From (27a), the loss of consumers depends on the price elasticity of demand, β_d. It also depends on the level of future profit discount level , r_d. If the firm discounts heavily future profits, then the firm will not consider the increased loss of customers in the long run, but instead it will focus on the increased short run profits. The incumbent firm increases its price if $\frac{\partial \Pi(P,N)}{\partial P_d} > \frac{\partial \Pi(P,N)}{\partial N_d} \frac{\beta_d \alpha_D}{r_d}$. Therefore, the firm will choose an optimal pricing path ,$P_d(t)$, that balances the effects on short run profits and future profits.

Optimal Size and Pricing Path

From the first order conditions, the following second order differential equation is obtained;

$$\ddot{N}_d - r_d \dot{N}_d - \frac{r_d + 2c_d \beta_d \alpha_D (1-\rho)^2 + 2\beta_d \alpha_D \nu}{2\phi \beta_d \alpha_D} N_d = -\beta_d \alpha_D \frac{\frac{1}{\eta} P_e - a_d - 2c\rho(1-\rho)M - 2c(1-\rho)^2 N_e}{2\phi \beta_d \alpha_D} \tag{29}$$

This is a non-homogeneous second order differential equation, it will be solved in two steps. From (29) let;

$$k = \frac{r_d + 2c_d \beta_d \alpha_D (1-\rho)^2 + 2\beta_d \alpha_D \nu}{2\phi \beta_d \alpha_D}$$

$$d = -\beta_d \alpha_D \frac{\frac{1}{\eta} P_e - a_d - 2c_d \rho(1-\rho)M - 2c(1-\rho)^2 N_e}{2\phi \beta_d \alpha_D}$$

The second order differential equation can be re-written as;

$$\ddot{N}_d - r_d \dot{N}_d - kN_d = d$$

The solution of this differential equation is given by;

$$N_d(t) = (N_{d0} - N_d^*) e^{-r_d(\frac{\zeta_d - 1}{2})t} + N_d^* \tag{30}$$

where $\zeta_d = [1 + 2\frac{(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)}{(\phi\beta_d\alpha_D r_d^2)}]^{\frac{1}{2}}$ with $\zeta_d > 1$[1] and ,

$$N_d^* = \beta_d\alpha_D \frac{\frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c_d(1-\rho)^2 N_e}{r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu} \tag{31}$$

From (15a) and (29) the optimal pricing path is given by;

$$P_d(t) = \frac{1}{\eta}P_e + \frac{r_d}{\beta_d\alpha_D}\frac{\zeta_d - 1}{2}(N_{d0} - N_d^*)e^{-r_d(\frac{\zeta_d-1}{2})t} \tag{32}$$

Where the steady state price ,P_d^* is given by;
$\Rightarrow$

$$P_d^* = \frac{P_e^*}{\eta}$$

4.3.2 Entrant Profit Maximization

Let the cost function for the incumbent utility be defined as;

$$C_e(N_e) = F_e + a_e N_e + c_e N_e^2 + \nu N_e^2 + \phi \dot{N}_e^2 \quad a_e > 0, \quad c_e > 0 \quad \nu > 0, \quad F_e \geq 0 \tag{33}$$

The entrant utility's long run profit maximization problem is defined as follows;

$$\max_{P_e(t)} \Pi_e(t) = \int_0^\infty e^{-r_e t}[(1-\tau)P_e N_e - C_e(N)]dt \tag{34}$$

subject to
(a) $\dot{N}_e = \beta_d\alpha_E[P_d(t) - \frac{1}{\eta}P_e(t)]$,
(b) $N_e(0) = Ne_0$
(c) $N(t) = N_d(t) + N_e(t)$
(d) $lim_{t\to\infty}[N_e(t)e^{-r_e t}] = 0$.

The Hamiltonian for this problem is given by :

$$H(N_e, P_e, T, \lambda_e) = e^{-r_e t}\Pi_e(P_e, N_e) + \beta_d\alpha_E[P_d(t) - \frac{1}{\eta}P_e(t)] \tag{35}$$

Where,
$\Pi_e(P_e, N_e) = (1-\tau)P_e N_e - C_e(N_e)$ and $\lambda_e(t)$, is the Lagrange multiplier associated with 35(a). Here the Lagrange multiplier is interpreted as the shadow price , which is the value to the utility for an extra customer at time,t.
From equation(11) we have the following first order conditions necessary for intertemporal

[1]Since all the parameters are positive , thus $(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu) > 0$. The denominator has positive parameters, therefore $(\phi\beta_d\alpha_D r_d^2 > 0$. Thus $2\frac{(r_d+2c_d\beta_d\alpha_D(1-\rho)^2+2\beta_d\alpha_D\nu)}{(\phi\beta_d\alpha_D r_d^2}> 0$ and $\zeta_d > 1$

maximization problem;

$$\frac{\partial H}{\partial P_e} = H_{P_e} = e^{-r_e t}((1-\tau)N_e + 2\phi\beta_d^2\alpha_E^2[P_d(t) - \frac{1}{\eta}P_e]) - \lambda_e\beta_e\alpha_E = 0 \tag{36}$$

$$\frac{\partial H}{\partial N_e} = H_{N_e} = e^{-r_e t}((1-\tau)P_e - \dot{C}_e(N_e)) = -\dot{\lambda}_e \tag{37}$$

We define the current Hamiltonian as in the case of the incumbent firm. By the same derivation, the following results stands;

Lemma 7 *The first order condition of H^c at the optimum is given by;*

$$\frac{\partial \Pi(P_e, N_e)}{\partial P_e} = \frac{\beta_d\alpha_E}{\eta r_e}\frac{\partial \Pi(P_e, N_e)}{\partial N_e} \tag{38 a}$$

Proof. As shown in Lemma 1.2 ■

Optimal Size and Pricing Path

Differentiating (36) with respect to, t,and substituting for λ_e and $\dot{\lambda}_e$ in (37)to derive the second-order differential equation in N_e.

$$\ddot{N}_e - r_e\dot{N}_e - \frac{\eta r_e(1-\tau) + 2c_e\beta_d\alpha_E + 2\beta_d\alpha_E\nu}{2\phi\beta_d\alpha_E}N_e = -\beta_d\alpha_E\frac{\eta(1-\tau)P_d - a_e}{2\phi\beta_d\alpha_E} \tag{39}$$

This is a non-homogenous second order differential equation, we solve this in two steps. From (39) let;

$$k = \frac{\eta r_e(1-\tau) + 2c_e\beta_d\alpha_E + 2\beta_d\alpha_E\nu}{2\phi\beta_d\alpha_E}$$

$$d = -\beta_d\alpha_E\frac{\eta(1-\tau)P_d - a_e}{2\phi\beta_d\alpha_E}$$

The solution of this differential equation is given by;

$$N_e(t) = (N_{e0} - N_e^*)e^{-r_e(\frac{\zeta_e - 1}{2})t} + N_e^* \tag{40}$$

where $\zeta_e = [1 + 2\frac{(\eta r_e(1-\tau) + 2c_e\beta_d\alpha_E + 2\beta_d\alpha_E\nu)}{(\phi\beta_d\alpha_E r_e^2)}]^{\frac{1}{2}}$ with $\zeta_e > 1$[2]

$$N_e^* = \beta_d\alpha_E\frac{\eta(1-\tau)P_d - a_e}{\eta r_e(1-\tau) + 2c_e\beta_d\alpha_E + 2\beta_d\alpha_E\nu} \tag{41}$$

[2]proof similar to [1]

From (34a) and (40) the optimal pricing path is given by;

$$P_e(t) = \eta(1-\tau)P_d(t) + \frac{\eta r_e}{\beta_d \alpha_E}\frac{\zeta_e - 1}{2}(N_{e0} - N_e^*)e^{-r_e(\frac{\zeta_e-1}{2})t} \tag{42}$$

Where the steady state price , P_e^* is given by; $\Rightarrow$

$$P_e^* = \eta(1-\tau)P_d$$

4.4 Case Analysis

The optimal pricing path for both the incumbent and the entrant firm show the strategic interaction between the two firms over time. Specifically, each firm responds to the price set by its competitor. This is in contrast with the pricing path followed by the monopoly in the [81]. It is this strategic interaction between the two firms that can lead to perfect competition under specific parameter conditions. The role of the policy maker can be one that shifts the equilibrium to a perfectly competitive equilibrium. The relative network size scenarios analyzed in this paper creates 9 possible pricing path, $\{S_e, S_d\}$, $\{S_e, C_d\}$, $\{S_e, G_d\}$, $\{C_e, S_d\}$, $\{C_e, C_d\}$,$\{C_e, G_d\}$,$\{G_e, S_d\}$,$\{G_e, C_d\}$, and $\{G_e, G_d\}$. Under the assumption that the entrant firm has an initial network size of , $N_{e0} = 0$, then we can eliminate the following cases from our analysis; $\{G_e, S_d\}$, $\{S_e, S_d\}$, $\{C_e, G_d\}$ and $\{C_e, C_d\}$. Under this assumption, competition only exists if the entrant firm can grow its network size. This reduces the cases to be analyzed to the following; $\{G_e, S_d\}$,$\{G_e, C_d\}$, and $\{G_e, G_d\}$. The case of , $\{G_e, S_d\}$, can be achieved by both an increase in prices by both firms or in this case only the entrant is choosing prices that are lower than that of the incumbent form. The case of , $\{G_e, G_d\}$, is one in which both firms are raising their prices. evolution of the pricing path in this case is analyzed in the following paragraphs. The case of, $\{G_e, C_d\}$, can be achieved when both firms follow an increasing pricing path. The following table summarizes the case analysis in terms of the pricing path;

Table 4.6: Pricing Path

	G_d	C_d	S_d
G_e	$\uparrow$ P	$P_d = \frac{P_e}{\eta}$	?
S_e	N/A	N/A	$\downarrow$P

One can note that in the case G_e, C_d, we have $(N_{d0} - N_d^*) = 0$ therefore $P_d(t) = \frac{1}{\eta}P_e(t)$, in this case the incumbent firm initial prices are only adjusted for the price responsiveness of the customers between the entrant firm and the incumbent firm. In the case, G_e, S_d,we have $(N_{d0} - N_d^*) > 0$ therefore $P_d(t) = \frac{1}{\eta}P_e + \frac{r_d}{\beta_d \alpha_D}\frac{\zeta_d - 1}{2}(N_{d0} - N_d^*)e^{-r_d(\frac{\zeta_d-1}{2})t} > P_e(t)$, in this case the incumbent firm always has prices higher than that of the entrant firm. These two cases though feasible , they are of less interest in terms of the analysis in this paper. The rest of the analysis focuses on the case $\{G_e, G_d\}$.

4.4.1 Comparative Statics Analysis

This section focuses on the sensitivity of the objective function values, control variables and state variables with respect to the parameters in the model. The partial derivatives used in all the analysis in this section were verified using **MATLAB**[3] function *diff* and the sign of the partial derivatives using the *isAlways* function.

Steady State Network Sizes

Incumbent Firm

The steady state network size of the incumbent firm is given by;

$$N_d^* = \beta_d \alpha_D \frac{\frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c(1-\rho)^2 N_e}{r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu} \tag{31}$$

By taking the first order conditions of N_d^* with respect to the model parameter, we describe how the steady state network size changes as these parameters change. Since $N_d^* > 0$, let $A = \frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c(1-\rho)^2 N_e > 0$. The following table summarizes the range of each parameter under consideration;

[3]The MATLAB code can be provided upon request

Table 4.7: Parameter Range Definition

Parameter	**Range**
A	$A > 0$
β_d	$0 < \beta_d < 1$
α_D	$0 < \alpha_D < 1$
α'_D	$-1 < \alpha'_D < 0$
N_e	$N_e > 0$
P_e	$P_e > 0$
λ_d	$0 < \lambda_d < 1$
ν	$0 < \nu < 1$
r_d	$0 < r_d < 1$
η	$\eta > 0$
c_d	$c_d > 0$
a_d	$a_d > 0$

The summary of the comparative analysis of the steady state network size is as follows;

- increases with P_e, if the competitive entrant increase its prices, consumers will prefer joining the incumbent utility network compared to the entrant's network. This results in a higher steady state network size for the incumbent.

$$\frac{\partial N_d^*}{\partial P_e} = \frac{\alpha_D \beta_d}{(\eta)(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)} > 0$$

- decreases with ν, as the environmental tax imposed on emissions increases, it becomes more expensive to generate electricity using fossil fuels, therefore any firm that uses fossil fuels for electricity generation incurs higher costs of production. Thus resulting in the firm setting higher prices ,P_d, which results in a reduction in the network size.

$$\frac{\partial N_d^*}{\partial \nu} = -\frac{(2\alpha_D^2\beta_d^2)(\frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c(1-\rho)^2N_e)}{(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)^2} < 0$$

- decreases with η, as ,η increases, the responsiveness of the market to the price set by the incumbent utility increases. Therefore consumers are more sensitive to any price increase implemented by the incumbent firm. This results in consumers preferring the entrant network compared to the incumbent's network. This implies that the network size of the incumbent is shrinking hence a lower steady state network size for the incumbent firm.

$$\frac{\partial N_d^*}{\partial \eta} = -\frac{P_e \alpha_D \beta_d}{(\eta^2)(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)} < 0$$

- decreases with N_e, since there is strategic interaction between the two firms, an increase in the entrant firms network size, N_e , this results in the loss of consumers by the incumbent firm. In other words, the consumers prefer the entrant utility to the incumbent utility.

$$\frac{\partial N_d^*}{\partial N_e} = -\frac{2\alpha_D\beta_d(1-\rho)^2}{r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu} < 0$$

- increases with α_D, intuitively as the market potential increases the number of available consumers to the incumbent firm is increasing. The firm can increase its steady state network size in a a market with higher potential , therefore the resultant steady state network size is higher.

$$\frac{\partial N_d^*}{\partial \alpha_D} = \frac{\beta_d(\frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c(1-\rho)^2N_e)}{r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu} - \frac{\alpha_D\beta_d(2\beta_d\nu + 2\beta_d c_d(1-\rho)^2)(\frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c(1-\rho)^2N_e)}{(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)^2} > 0$$

- decreases with r_d, as the incumbent firm discounts heavily future profits, it adopts high short run prices to achieve higher short term profits. This firm sacrifices long run profits to obtain higher short run profits, as a consequence, the incumbent firm will have a lower steady state network size.

$$\frac{\partial N_d^*}{\partial r_d} = -\frac{\alpha_D\beta_d(\frac{1}{\eta}P_e - a_d - 2c_d\rho(1-\rho)M - 2c(1-\rho)^2N_e)}{(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)^2} < 0$$

Entrant Firm

The steady state network size of the entrant firm is given by;

$$N_e^* = \beta_d\alpha_E \frac{\eta(1-\tau)P_d - a_e}{\eta(1-\tau)r_e + 2c_e\beta_d\alpha_E + 2\beta_d\alpha_E\nu} \quad (41)$$

Using the same assumptions as in the case of the incumbent firm, the following partial derivatives with respect to the parameters are as follows; $\frac{\partial N_e^*}{\partial P_d} > 0$,$\frac{\partial N_e^*}{\partial \nu} < 0$, $\frac{\partial N_e^*}{\partial \tau} < 0$, $\frac{\partial N_e^*}{\partial \alpha_E} > 0$ and $\frac{\partial N_e^*}{\partial r_e} < 0$ The analysis of these partial derivatives is similar to the analysis given for the incumbent firm.

Initial Prices

Incumbent Firm

The initial price for the incumbent firm is given by;

$$P_d(0) = \frac{1}{\eta}P_e(0) + \frac{r_d}{\beta_d \alpha_D}\frac{\zeta_d - 1}{2}(N_{d0} - N_d^*) \tag{43}$$

Since $(N_{d0} - N_d^*) < 0$ the prices set by the incumbent firm is lower than $\frac{1}{\eta}P_e(0)$. Each firm 's initial price also depends on the responsiveness of the consumers to the price set by each firm. There are three cases since $\eta \gtreqless 1$. When $\eta > 1$, then $P_d(0)$ is lower since consumers are more responsive to the price set by the incumbent, thus a higher initial price will result in loss of consumers to the entrant firm. When $\eta < 1$, then $P_d(0)$ is higher since consumers are less responsive to the price set by the incumbent, thus a higher initial price will not result in a loss in customers.

When $\eta = 1$, the incumbent's firm initial price lower than P_e is proportional to $(N_{d0} - N_d^*)$ with a proportionality constant $\frac{r_d}{\beta_d \alpha_D}\frac{\zeta_d - 1}{2}$ with $\zeta_d = [1 + 2\frac{(r_d + 2c_d\beta_d\alpha_D(1-\rho)^2 + 2\beta_d\alpha_D\nu)}{\phi\beta_d\alpha_D r_d^2}]^{\frac{1}{2}}$. The following summarizes the amount by which the incumbent firm's prices will be lower than the price set by the entrant firm:

- decreases with r_d, if the firm discounts heavily on the future profits, then the initial prices it sets will be high to achieve higher short run profits. This is because the strategy of charging lower than the entrant firm is less appealing to the incumbent , so it adopts a higher initial price.

- decreases with β_d, Since β_d is a measure of the responsiveness of the consumers to the price differential between the two firms. As the price elasticity of demand for the incumbent utility increases, i.e the consumers of the become more sensitive to the price differential between the two firms, then the incumbent firm can adopt an initial price that is close to the initial price of the entrant and still achieve an increase in the network size and high long run profits.

- decreases with ρ, as the amount of theft increases, the cost of energy production for the incumbent increases. Therefore, the incumbent has little incentive to charge lower prices, and it adopts an initial price that is close to the initial price of the entrant firm.

- decreases with ν, as the environmental tax charged on the firm increases, the cost of electricity generation increases for the firm. In order to maintain specific levels of profit, the firm has to raise its prices hence reducing the level of price differential between the two firms.

- decreases with ϕ, as the adjustment costs increases the incumbent firm has less incentive to charge prices that are significantly less than the prices charged by the entrant as it is costly. The incumbent will adopt initial prices that are slightly lower than the price of the entrant firm. This is true for any point in time in the planning horizon.

- decreases with c_d,as the marginal cost of production increases, the cost of electricity generation increases for the firm. In order to maintain specific levels of profit, the firm has to raise its prices hence reducing the level of price differential between the two firms.

Entrant Firm

While that of the entrant firm is given as follows;

$$P_e(0) = \eta(1-\tau)P_d(0) + \frac{\eta r_e}{\beta_d \alpha_E} \frac{\zeta_e - 1}{2}(N_{e0} - N_e^*) \tag{44}$$

Since $(N_{e0} - N_e^*) < 0$ in the case, G_e, G_d, the prices set by the entrant firm is lower than $\eta P_d(0)$. Each firm 's initial price also depends on the responsiveness of the consumers to the price set by each firm. There are three cases since $\eta \gtreqless 1$. When $\eta > 1$, then $P_e(0)$ is higher since consumers are more responsive to the price set by the incumbent, thus a higher initial price will not result in loss of consumers by the entrant firm. When $\eta < 1$, then $P_e(0)$ is less since consumers are more responsive to the price set by the entrant, thus a higher initial price will result in a loss of consumers.
When $\eta = 1$, the entrant firm's initial price lower than $P_d(0)$ is proportional to $(N_{e0} - N_e^*)$ with a proportionality constant $\frac{\eta r_e}{\beta_d \alpha_E} \frac{\zeta_e - 1}{2}$ with $[1 + 2\frac{(\eta(1-\tau)r_e + 2c_e\beta_d\alpha_E + 2\beta_d\alpha_E\nu)}{\phi\beta_d\alpha_E r_e^2}]^{\frac{1}{2}}$. The following summarizes the amount by which the entrant firm's prices will be lower than the price set by the incumbent firm:

- decreases with r_e, if the firm discounts heavily on the future profits, then the initial prices it sets will be high to achieve higher short run profits. This is because the strategy of charging lower than the incumbent firm is less appealing to the entrant , so it adopts a higher initial price.

- decreases with β_d, as the price elasticity of demand for the incumbent utility increases, i.e the consumers of the incumbent become more sensitive to the price differential between the two firm, then the entrant firm can adopt an initial price that is close to the initial price of the incumbent and still achieve an increase in the network size and high long run profits. This is true for a fixed η.

- decreases with ν, as the environmental tax charged on the firm increases, the cost of electricity generation increases for the firm. In order to maintain specific levels of profit, the firm has to raise its prices hence reducing the level of price differential between the two firms.

- decreases with ϕ, as the adjustment costs increases the entrant firm has less incentive to charge prices that are significantly less than the prices charged by the entrant as it is more costly. The entrant will adopt initial prices that are slightly lower than the price of the incumbent firm. This is true for any point in time in the planning horizon.

- decreases with c_e, as the marginal cost of production increases, the cost of electricity generation increases for the firm. In order to maintain specific levels of profit, the firm has to raise its prices hence reducing the level of price differential between the two firms.

Steady State Prices

From the pricing path of the incumbent and the entrant, the steady state prices converge to the following;

$$P_e^* = \eta(1-\tau)P_d^* \tag{45}$$

If $\tau = 0$

The entrant firm receives all the revenue made from the sell of its energy. This is true in the case where the entrant firm collects its own revenue directly from its consumers or the grid operators it sells its energy to pays all the revenue it owes to the entrant. The latter case is less common in developing countries. We re-write equation (18) as follows;

$$P_{e_{\tau=0}}^* = \eta P_d^* \tag{46}$$

Recall, $\beta_d = \eta\beta_e$. Since $\eta \gtreqless 1$, there are three possible pricing levels for each firm.

When $\eta = 1$, this means that the consumers are equally responsive to the pricing changes implemented by both the incumbent and the entrant firm. In order to maximize long run profits and increase network size, both firms converge to the same price, $P_{e_{\tau=0}}^* = P_d^*$. In this case , no firm has any advantage over the other. Therefore, at the steady state, this market is a perfectly competitive market, and hence the market players are price takers and $P_{e_{\tau=0}}^* = P_d^*$ is the market price for electricity.

When $\eta > 1$, then $\beta_d > \beta_e$, the price elasticity of demand is higher for the incumbent compared to the entrant firm. This can be due to a history of poor service provision by the incumbent utility. Since $P_{e_{\tau=0}}^* = \eta P_d^*$, then $P_{e_{\tau=0}}^* > P_d^*$. The entrant firm has a pricing advantage due to the higher price elasticity of demand for the incumbent.

When $\eta < 1$, then $\beta_d < \beta_e$, the price elasticity of demand is higher for the entrant compared to the incumbent firm. This can be due to market inertia and a good reputation for the incumbent utility. Therefore consumers are more likely to stay put with the incumbent utility but are more sensitive to the price levels set by the entrant firm. Since $P^*_{e_{\tau=0}} = \eta P^*_d$, then $P^*_{e_{\tau=0}} < P^*_d$. The incumbent firm has a pricing advantage due to the higher price elasticity of demand for the entrant.

If $\tau > 0$

This means that a fraction of the revenue owed to the supplier by the government is not paid to the utility. This is common in markets with poor government systems i.e developing countries. Let equation(18) be ;

$$P^*_{e_{\tau>0}} = \eta(1-\tau)P^*_d \tag{47}$$

The same analysis that is given for the relationship between P^*_e and P^*_d when $\tau = 0$ applies for the case when $\tau > 0$.However, for any value of the η , the entrant firm ends up with lower revenue than the incumbent utility.

Lemma 8 *For any η , $P^*_{e_{\tau=0}} > P^*_{e_{\tau>0}}$*

Proof. This follows from (46),(47) and the definition of τ, which is , $0 < \tau < 1$. ■ It is counter-intuitive that$P^*_{e_{\tau=0}} > P^*_{e_{\tau>0}}$, but when the entrant firm does not realize all the revenue , it has to maximize its network size in-order to maximize its profits. This implies that for the firm to maintain a certain level of profits, it should be the case that $N^*_{e_{\tau=0}} < N^*_{e_{\tau>0}}$. This is achieved by following a lower pricing path compared to the case where it realizes all the revenue hence $P^*_{e_{\tau=0}} > P^*_{e_{\tau>0}}$. It is very important to have structures that guarantee that the entrant firms receive their revenue either by ensuring payment on time or allowing the entrant firm to collect its own revenue from the consumers it serves. This guarantees that no firm has a competitive advantage and makes it attractive for new firms to enter the market.

4.5 Conclusions

This study presented an inter-temporal framework for analyzing the pricing path that can be employed by a competitive incumbent and a competitive market entrant in the electricity markets of developing economies. It provided a policy framework that is consistent with the policy needs in developing economies i.e encouraging participation of private players in the electricity markets and provided a profitable framework that can be implemented by new investors. This study also provided a robust extension of the theoretical framework introduced by Chisari. Market players employ an increasing pricing path that converge to the steady state prices of competitors. In this case, the market detects the prices charged to the consumers. This pricing path is affected by both endogenous and exogenous conditions which in turn affect the steady state network size of each utility. This analysis was carried out by considering assumptions such as network adjustment costs and theft of service as in [81]. It was shown that the entrant can maximize its long run profits by adopting low future profit discounts. This allows the firm to hold its prices below the prices that are employed by the incumbent utility. When the price of the incumbent utility is fixed, the entrant will adopt an increasing pricing path that will converge to the incumbent firm's price. Otherwise, the entrant firm will always adopt lower prices than the incumbent firm. The pricing path of the entrant is also affected by the degree at which the entrant discount future profits. A firm with high discounts rates values the short run profits therefore it exercises less restraint on charging high prices. In contrast, a firm with lower discounts rates can exercise higher restraint on the prices it adopts. This firm will enjoy larger long run profits and network size compared to the firm with higher discount rates. The analytical results obtained can be used to shape pricing policy in developing countries and also inform the market players on the optimal pricing path. This problem can also be analyzed using the Stackelberg model in which the dominant incumbent is the leader while the entrant is the follower.

Chapter 5

Optimal Taxing Strategy to Increase Competitiveness of Green Utility Suppliers: A Theoretical Framework

5.1 Introduction

Over the past two decades there has been a shift in government policies in order to reduce the carbon footprint. A total of 160 nations reached an agreement called the Kyoto Protocol, which encourages all industrialized nation to put in places protocols to reduce carbon emissions [125]. The countries that entered into this agreement are at different levels of addressing the carbon footprint problem. One of the main contributors of carbon dioxide emissions is electricity generation. The United State Environmental Protection Agency(EPA) reported that 25 % of the global carbon dioxide emission come from electricity and heat generation. This is the largest contribution to the carbon dioxide emissions compared to any other economic sector. Most nations have passed legislation to adopt a renewable energy policy strategy. However most countries face the problem of barriers to entry for new renewable utilities. There are financial and economic barriers to entry; The initial capital cost of renewable energy is higher compared to the capital costs of conventional energy sources [128]. A direct consequence of the higher generation costs are higher unit prices, which tend to be highly unaffordable in most cases [130]. This renders renewable utility firms less attractive and less competitive in comparison to the incumbent firms using conventional energy sources. It is important to investors to have lower investments costs while maximizing profits. The high cost of generation makes renewable energy less competitive in a market where conventional sources provide a cheaper and readily available alternative. An additional barrier to entry of renewable energy utilities is observed on the policy level. The lack of well developed policies is a big barrier to entry of renewable energy. The capital intensive renewable sector requires a robust policy framework in order to attract investors into this market. Well defined policies and regulations help mitigate the levels of risk that come with investing in renewable energy technologies [129]. There exists other barriers to entry of renewable energy like technical barriers, social, cultural, financial, geographical and ecological barrier. Can the policy maker or government create a policy framework that make renewable source competitive relative to conventional sources? There is vast literature on the implementation of subsidy to level the the competitive field for environmentally friendly technologies in terms of market price [131, 132, 133]. Introducing subsidies helps new technologies to implement pricing paths that makes the new technology competitive to the conventional or already existing technologies. While developed economies can afford subsidies on renewable energy technology development, can developing economies afford the implementing the subsidy policy? Most industrialized economies already provide subsidies for electricity, however the majority of these countries, if not all, are aware of the questionable benefits of the subsidy policy [134] .

Instead of increasing the fiscal burden on the government by providing additional and more expensive subsidies on renewable energy, the government can implement a taxing policy on fossil fuels in order to make renewable utilities competitive in terms of market price. This paper provides a theoretical framework to determine an optimal taxing strategy that improves the competitiveness of renewable utilities and the in/direct social gains from implementing such a taxing strategy. The social costs includes lower yields due to changing weather patterns, lung ailments, acid rain etc. These social costs can be country specific and can be specified by policy makers in each respective country.

5.2 Literature Review

The benefits of using renewable energy are well documented; this includes the slowing down of climate change to maintaining agricultural productivity in developing and developed economies. However, there is strong evidence that suggests the cost intensive nature of adopting renewable energy sources [135]. The high investments cost for renewable energy generation makes renewable energy highly unaffordable in developing economies [130], and as a result this makes renewable utilities less competitive in terms of consumer penetration. Leveraging the competitive field for newer technologies has been a large part of economics research. There is evidence that suggests that subsidizing green technology may help accelerate the penetration of green technology into the market [124]. Providing subsidies is especially challenging in developing economies where there are tighter constraints on the budget.

One of the main motivations for providing subsidies is to make electricity more affordable for the poor members of the population and create a form of redistribution of income or wealth to the poor. The extent of the benefit or redistribution due to subsidies has always been in question. This especially so in developing economies that have low levels of electricity access. In Sub-Saharan Africa, only 62.5 % of the population has access to electricity supply [136]; any form of electricity subsidy is not redistributed to the other 37.5% of the population. The population that does not have access to electricity tends to be the poorest amongst these populations. Experts have provided evidence that shows less than 10% of energy subsidies benefit the lowest fifth of the population by earnings, while more than 40% of the benefits goes to the top fifth in terms of earnings [134]. This makes energy subsidies an ineffective way of addressing poverty in developing countries.

Given the questionable benefits of subsidies on conventional sources of electricity and the financial pressure it exerts on the government budget, it can be inferred that subsidizing the more expensive renewable energy can be beyond the reach of some developing economies. It is also important to develop a different policy that that allows economical efficiency and can lead to a fairer redistribution of income to the entire population. One method of minimizing the competitive edge of conventional fuels is to introduce a tax on emissions. Introducing an emission tax (Carbon tax) leads to an increase in products and service that require the use of electricity. These price increases have a bigger impact on the low income households, since they spend a large part of their income on carbon intensive goods [138, 139, 140, 141]. The argument for a subsidy policy is that it does not the effect of an added burden on the low income households through an increase in prices. Wier showed empirically, in the case of Denmark, that the direct incidences of a carbon tax are regressive [137]. The same results were shown for the case of the United States [142, 144]. An extensive review of the literature on fuel taxes and inequality is given in [145]. The increases in prices can be mitigated by an efficient redistribution of the income from the tax policy or revenue recycling. Therefore, it is upon the policy makers to create an efficient redistribution or revenue recycling policy.

Bento shows empirically that the distributional impacts of a fuel tax U.S. is heavily dependent on the revenue recycling [146, 147]. Using data from the 1994 Consumer Expenditure Survey (CES), Metcalf finds the pure incidence of a carbon tax to be regressive. He proposed a payroll tax rebate policy that can counter the regressive incidence of a carbon tax [143]. Using multiple sets of CES data, West and Williams, finds when the labor tax rebates is implemented , only the the efficiency can be increased while regressivity is only reduced but not fully countered or neutralized. Other studies show empirically evidence that the regressive nature of a carbon or fuel tax can be reduced or neutralized by implementing strategic revenue recycling methods [148, 149]. While the focus of this paper is on redistribution of income, it is important to note the economic advantages that are presented by the use of a tax policy , in this case, to increase competition in the market for expensive technologies that are beneficial to society.

To summarize, this paper focuses on the determination of an optimal taxing strategy that minimizes social costs due to externalities from fossil fuels and renewable energy utilities. It also provides insight on how the utilities respond through their market prices to the introduction of a tax policy that targets one technology. In this case both firms have a fixed type of technology for electricity generation. While it can be argued that there firms can have utilities can have a mixture of technologies to produce energy, the separation of the two is sufficient for theoretical purposes. This paper does not focus on the redistribution of income through taxes, but rather it provides a theoretical alternative to governments that cannot afford the huge subsidies required for expensive renewable technology. This alternative is based of the failure or the questionable economic benefits that subsidy policies provide given the heavy financial burden they places on the government.

5.3 Model

This paper considers a duopoly in the electricity market in a developing economy. The government or policy makers in this setting are looking for strategies to increase the penetration of green energy or make green utility suppliers more competitive. Instead of introducing subsidies as in [124]. Consider an incumbent utility in most developing economies, this incumbent utility uses fossil fuels for generation of electricity. The government or policy maker places a tax , ψ_d on the purchase of the fossil generated energy. The consumer does not pay p_d, instead the consumer pays $p_d + \psi_d$. The new utility supplier uses renewable sources for electricity generation, e.g solar or wind energy. The entrant firm using renewable energy sources does not face taxes, therefore the consumers pay p_e. Let e= entrant firm and d= incumbent firm. The demand rate for the entrant firm supply and the incumbent firm supply are defined similar to the demand function in Spence 1976 [126];

$$\dot{N}_e = k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)] \tag{5.1}$$

$$\dot{N}_d = k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t) \tag{5.2}$$

Where $N_e(t)$ and $N_d(t)$ represents the network size of the entrant firm and the incumbent firm respectively. θ_e and θ_d represents the importance of clean energy to the consumers, it can be argued that as the population gains more knowledge on the effects of greenhouse gases to climate change the following is true; $\frac{d\theta_e}{dt} < 0$ and $\frac{d\theta_d}{dt} > 0$. β_e and β_d are the price responsiveness of the consumers to the price levels of the competitor. While k_e and k_d are constants. Assuming that the prices and demand for both utilities are positive, then $\theta_e\theta_d - \beta_e\beta_d > 0$.

The next part of the model formulation is the definition of the unit cost functions for both firms. The incumbent which uses fossil fuel for energy generation adopts the following function $C(N_d,t) = {c_d}^0 + c_d N_d(t)^2$ while the entrant firm adopts the following cost function $C(N_e,t) = {c_e}^0 - c_e N_e(t)$. Where ${c_d}^0, c_d, {c_e}^0, c_e$ are positive constants and ${c_e}^0 > {c_d}^0$. This implies that initially the entrant firm has incurs higher unit costs compared to the incumbent firm. However, as the network size of the entrant firm increases its unit costs decreases while the incumbent firm faces unit costs that are increasing at an increasing rate.

The unit cost functions shows that initially the entrant firm has a cost disadvantage compared to the incumbent firm using fossil fuels. This might translate to a pricing advantage to the incumbent firm over the entrant firm. The government or policy maker seeks to address this

challenge by introducing an emission tax ,$\psi(t)$, that will only affect the incumbent firm. In this paper the tax, $\psi(t)$, is not included in the unit cost function but as a price perturbation for the incumbent firm. This is similar to the subsidy model in [124]. Given that both firms know the existence of the government tax on the incumbent firm, the firms adjust their pricing path accordingly in order to maximize their profits. The taxes that are collected from the incumbent firm can be a lump sum pay to the society. This will be included in the social cost objective function. The cumulative tax collected over a period [0, T], can be denoted as $\Psi(T) = \int_0^T \psi(t)\dot{N}_d dt \quad , \Psi(0) = 0$.
The use of fossil fuels comes with social costs chief amongst them is the changes in the climate. The productivity of weather dependent sectors like the agricultural sector will see major declines in productivity levels. Most developing economies heavily depends on agricultural productivity for gross domestic product(GDP), levels of employment and the quality of life, therefore a decline in agricultural productivity will have an adverse effect on the economy. The effects of lower agricultural productivity can also have an indirect negative effect on the economy as it affects the levels of income and consumption levels. There are social costs that come with renewable sources too, these costs might include the land required for solar farms and wind farms. The objective of the government is to minimize the social costs;

$$\min J_l = z_d N_d(T) + z_e N_e(T) - \Psi(T) \tag{5.3}$$

Where z_d and z_e are unit cost assigned to the different sources of energy based on the preference of the policy maker. The actually weights can be assigned using different ranking methods. The weights can be determined by using the Analytic Hierachy Process(AHP) developed by Saaty in 1980 [127]. The AHP method works well for ranking problems that involve multiple decision makers. For a government that weighs heavily the impacts of climate change on its economy , then $z_d > z_e$.

5.4 The Strategic Set Up

The game is set up as a Stackelberg differential game where the policymaker is the leader and the two firms are the followers. This means that the policymaker has to determine before hand the the taxing strategy that will help improve the competitiveness of the green utility supplier. Given this taxing strategy both firms compete on price, which is the control variable for both firms. In order to solve for the optimal taxing strategy, the followers problem is solved first then the leaders problem can be solved. The inverse demand functions for both the entrant and the incumbent firm , gives the strategic interaction between the two firms; high market prices by either firm increases the the demand rate for its competitor.

5.4.1 The Entrant Firm Strategy

The objective of the entrant firm is to maximize its profit during the duration of the favorable taxing strategy by the policy maker. The entrant optimal problem is;

$$\max_{p_e} \Pi_e = \int_0^T [k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)](p_e(t) - c_e{}^0 + c_e N_e(t))dt \quad (4)$$

$$\text{subject to}$$
$$\dot{N}_e = k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)]$$
$$\dot{N}_d = k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)$$
$$p_e(t) > 0$$

Let the Hamiltonian function be;

$$\begin{aligned}\mathscr{H}_e = [k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)](p_e(t) - c_e^0 + c_e N_e(t)) + \\ \lambda_e^e[k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)] + \lambda_e^d[k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)]\end{aligned} \quad (5.4)$$

From the maximum principle, the following first order conditions are derived;
$\dot{\lambda}_e^e = -\frac{\partial \mathscr{H}_e}{\partial N_e} = -c_e[k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)] = -c_e \dot{N}_e$
$\dot{\lambda}_e^d = -\frac{\partial \mathscr{H}_e}{\partial N_d} = 0$
Using the transversality conditions $\lambda_e^e(T) = 0$ and $\lambda_e^d(T) = 0$ and from the first order conditions of the costates;

$$\lambda_e^e(t) = -c_e N_e(t) + \lambda_e^{e0} \Rightarrow \lambda_e^{e0} = c_e N_e(T)$$

$$\lambda_e^d(t) = \lambda_e^{d0} \Rightarrow \lambda_e^{d0} = 0$$

Where λ_e^{e0} and λ_e^{d0} are constants.
Since price is the control variable, the Hamiltonian maximizing condition is;

$$\frac{\partial \mathscr{H}_e}{\partial p_e} = -\theta_e[p_e - c_e^0 + c_e N_e] + [k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)] - \theta_e \lambda_e^e + \beta_d \lambda_e^d = 0 \quad (5.5)$$

Using equation (5) and the transversality conditions, we derive;

$$2\theta_e p_e - \beta_e \psi_d - \beta_e p_d = \theta_e(c_e^0 - \lambda_e^{e0}) + k_e \quad (5.6)$$

5.4.2 The Incumbent Firm Strategy

The objective of the incumbent firm is to maximize its profit during the duration of the favorable taxing strategy by the policy maker. The incumbent optimal problem is;

$$\max_{p_d} \Pi_d = \int_0^T [k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)](p_d(t) - c_d{}^0 - c_d N_d(t)^2)dt \qquad (7)$$

$$\text{subject to}$$

$$\dot{N}_d = k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)$$

$$\dot{N}_e = k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)]$$

$$p_d(t) > 0$$

Let the Hamiltonian function be;

$$\mathscr{H}_d = [k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)](p_d(t) - c_d{}^0 - c_d N_d(t)^2) + \lambda_d^e[k_e - \theta_e p_e(t) + \beta_e[p_d(t) + \psi_d(t)] + \lambda_d^d[k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)] \qquad (5.7)$$

From the maximum principle, the following first order conditions are derived;

$\dot{\lambda}_d^d = -\frac{\partial \mathscr{H}_d}{\partial N_d} = 2c_d[k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)] = 2c_d \dot{N}_d$

$\dot{\lambda}_d^e = -\frac{\partial \mathscr{H}_d}{\partial N_e} = 0$

Using the transversality conditions $\lambda_d^d(T) = 0$ and $\lambda_d^e(T) = 0$ and from the first order conditions of the costates;

$$\lambda_d^d(t) = 2c_d N_d(t) + \lambda_d^{d0} \Rightarrow \lambda_d^{d0} = -2c_d N_d(T)$$

$$\lambda_d^e(t) = \lambda_d^{e0} \Rightarrow \lambda_d^{e0} = 0$$

Where λ_d^{d0} and λ_d^{e0} are constants.

Since price is the control variable, the Hamiltonian maximizing condition is;

$$\frac{\partial \mathscr{H}_d}{\partial p_d} = -\theta_d[p_d - c_d{}^0 - c_d N_d(t)^2] + [k_d - \theta_d[p_d(t) + \psi_d(t)] + \beta_d p_e(t)] - \theta_d \lambda_d^d + \beta_d \lambda_d^e = 0 \qquad (5.8)$$

Using equation (8) and the transversality conditions, we derive;

$$2\theta_d p_d - \theta_d \psi_d - \beta_d p_e = \theta_d(c_d^0 + c_d N_d^2 - 2c_d N_d - \lambda_d^{d0}) + k_d \qquad (5.9)$$

Proposition 1 *The optimal pricing path for the entrant firm and the incumbent firm are given by the the following;*

$$p_e^*(t) = \frac{1}{4\theta_e\theta_d - \beta_e\beta_d}\Big\{\beta_e\theta_d[c_d^0 + c_d N_d^2 - 2c_d N_d - \lambda_d^{d0} + \psi_d] + 2\theta_d\theta_e(c_e^0 - \lambda_e^{e0}) + 2\theta_d k_e + \beta_e k_d\Big\} \quad (5.10)$$

$$p_d^*(t) = \frac{1}{4\theta_e\theta_d - \beta_e\beta_d}\Big\{\psi_d[\beta_d\beta_e - 2\theta_e\theta_d] + \beta_d\theta_e(c_e^0 - \lambda_e^{e0}) + 2\theta_d\theta_e(c_d^0 + c_d N_d^2 - 2c_d N_d - \lambda_d^{d0}) + 2\theta_e k_d + \beta_d k_e\Big\} \quad (5.11)$$

Proof. Solving the simultaneous equation from (5) and (9) gives Prop 1. ■

5.4.3 Policy Maker Strategy

The objective of the government or policymaker is to minimize the social cost due to electricity production from both the conventional fuels or renewable sources. The optimization problem for the policy maker is as follows;

$$\min J_l = z_d N_d(T) + z_e N_e(T) - \Psi(T)$$

The Hamiltonian equation for this problem is given as;

$$\mathscr{H}_l = \lambda_l^e \dot{N}_e(t) + \lambda_l^d \dot{N}_d(t) - \lambda_l^l \dot{\Psi}(t) + \Phi_l^e \dot{\lambda}_e^e + \Phi_l^d \dot{\lambda}_d^d$$
$$= (\lambda_l^e - c_e\Phi_l^e)[k_e - \theta_e p_e^* + \beta_e[p_d^* + \psi_d]] + (\lambda_l^d - \lambda_l^l\psi_d + 2c_d\Phi_l^d)[k_d - \theta_d[p_d^* + \psi_d] + \beta_d p_e^*]$$

From the Hamiltonian, costate equations are derived;

$$\dot{\lambda}_l^l = -\frac{\partial \mathscr{H}_l}{\partial \Psi(t)} = 0 \quad (5.12)$$

$$\dot{\lambda}_l^d = -\frac{\partial \mathscr{H}_l}{\partial \dot{N}_d} = -(\lambda_l^e - c_e\Phi_l^e)\frac{2N_d c_d\beta_e\theta_d\theta_e}{4\theta_e\theta_d - \beta_e\beta_d} + (\lambda_l^d - \lambda_l^l\psi_d + 2c_d\Phi_l^d)2c_d N_d\theta_d\frac{(2\theta_d\theta_e - \beta_e\beta_d)}{4\theta_e\theta_d - \beta_e\beta_d} \quad (5.13)$$

$$\dot{\lambda}_l^e = -\frac{\partial \mathscr{H}_l}{\partial \dot{N}_e} = -(\lambda_l^e - c_e\Phi_l^e)c_e\theta_e\frac{(2\theta_d\theta_e - \beta_e\beta_d)}{4\theta_e\theta_d - \beta_e\beta_d} + (\lambda_l^d - \lambda_l^l\psi_d + 2c_d\Phi_l^d)\beta_d c_e\frac{\theta_d\theta_e}{4\theta_e\theta_d - \beta_e\beta_d} \quad (5.14)$$

$$\dot{\Phi}_l^e = -\frac{\partial \mathscr{H}_l}{\partial \lambda_e^e} = -(\lambda_l^e - c_e\Phi_l^e)\theta_e\frac{(2\theta_d\theta_e - \beta_e\beta_d)}{4\theta_e\theta_d - \beta_e\beta_d} + (\lambda_l^d - \lambda_l^l\psi_d + 2c_d\Phi_l^d)\beta_d\frac{\theta_d\theta_e}{4\theta_e\theta_d - \beta_e\beta_d} \quad (5.15)$$

$$\dot{\Phi}_l^d = -\frac{\partial \mathscr{H}_l}{\partial \lambda_d^d} = (\lambda_l^e - c_e\Phi_l^e)\frac{\beta_e\theta_d\theta_e}{4\theta_e\theta_d - \beta_e\beta_d} - (\lambda_l^d - \lambda_l^l\psi_d + 2c_d\Phi_l^d)\theta_d\frac{(2\theta_d\theta_e - \beta_e\beta_d)}{4\theta_e\theta_d - \beta_e\beta_d} \quad (5.16)$$

Using equation (12) , we have $\lambda_l^l(t) = c$ where c is a constant.

The government control variable is the tax applied to fossil fuels, $\psi_d(t)$. The necessary optimality conditions for the policy maker gives;

$$\frac{\partial \mathscr{H}_l}{\partial \psi_d} = (\lambda_l^e - c_e\Phi_l^e)\frac{\beta_e\theta_d\theta_e}{4\theta_e\theta_d - \beta_e\beta_d} + (\lambda_l^d - \lambda_l^l\psi_d + 2c_d\Phi_l^d)\theta_d\frac{(\beta_e\beta_d - 2\theta_d\theta_e)}{4\theta_e\theta_d - \beta_e\beta_d} - \lambda_l^l[k_d - \theta_d[p_d^* + \psi_d] + \beta_d p_e^*] = 0 \quad (5.17)$$

Using the following transversality conditions; $\lambda_l^e(T) = z_e$, $\lambda_l^d(T) = z_d$, $\Phi_l^e(T) = 0$, $\Phi_l^d(T) = 0$ and $\lambda_l^l(T) = c$. These imply that the shadow price for an increase in one unit of the generation from either fossil fuels or renewable sources should equal the unit cost of either source as defined by z_e and z_d.

Proposition 2 *The optimal taxing strategy for the policy maker is given by the following;*

$$\psi_d^* = -\frac{z_e\beta_e\theta_e\theta_d}{(2\theta_d\theta_e - \beta_e\beta_d)(c + c\theta_d)} + \frac{z_d}{c + c\theta_d} + \frac{\theta_d(c_d^0 + c_dN_d^2 - 2c_dN_d - \lambda_d^{d0})}{1 + \theta_d} + \frac{2\theta_e\theta_dk_d + \beta_d\theta_e\theta_d(c^e - \lambda_e^{e0}) - \beta_dk_e(\theta_d - 2\theta_e)}{(2\theta_d\theta_e - \beta_e\beta_d)(1 + \theta_d)} \quad (5.18)$$

Proof. Using the transversality conditions above and solving equation (17) ■

5.5 Discussion and Analysis

In order to do a comparative analysis of the pricing path with respect to the changes in the tax level, differentiate (10) and (11) with respect to ψ_d. Given $\theta_e\theta_d - \beta_e\beta_d > 0$ one derives the following;

$$-1 < \frac{\partial p_d}{\partial \psi_d} = \frac{\beta_e\beta_d - 2\theta_e\theta_d}{4\theta_e\theta_d - \beta_e\beta_d} < 0 \quad (5.19)$$

$$\frac{\partial p_e}{\partial \psi_d} = \frac{\beta_e\theta_d}{4\theta_e\theta_d - \beta_e\beta_d} > 0 \quad (5.20)$$

This implies the following;

- The taxing policy forces the incumbent utility to reduce its marked price . This is a necessary strategy for the incumbent utility in order to stay competitive in the presence of the tax policy. The rate of decrease of the price is lower than the change in the tax level. This means that the tax policy is not the only instrument affecting the price level set by the incumbent firm. This allows the incumbent firm to remain competitive in the presence of such a tax policy.

- The entrant utility prices increase as the tax level on the incumbent utility increases. This potentially allows the entrant firm to be competitive without undercharging and failing to have reasonable investment returns.

The pricing strategies for both the entrant and the incumbent firms takes into account the presence of the tax policy. The tax collected from this set up reduces the social cost due to the effects of fossil fuel usage. This paper does not discuss the distribution of this tax amongst the population. However, it is important for the policy maker to design an efficient redistribution of income strategy. This is a challenge in developing countries where there are high levels of government corruption and poor governance structures. The changes in the taxing levels is also of interest. Differentiating the rate of change of the demands rates, $\dot{N}_e$ and $\dot{N}_d$ with respect to the tax level. First substitute (10) and (11) into (1) and (2) then differentiate with respect to the tax level to obtain;

$$\frac{\partial \dot{N}_e}{\partial \psi_d} = \frac{\beta_e \theta_e \theta_d}{4\theta_e \theta_d - \beta_e \beta_d} > 0 \tag{5.21}$$

$$\frac{\partial \dot{N}_d}{\partial \psi_d} = \frac{\beta_e \beta_d - 2\theta_e \theta_d}{4\theta_e \theta_d - \beta_e \beta_d} \theta_d < 0 \tag{5.22}$$

The expressions above imply that;

- As the tax level rises, the demand rate faced by the entrant utility increases. A higher tax on fossil generated energy implies that the overall cost of the energy from the incumbent utility increases. This increase in costs of acquiring fossil generated energy force the consumers to opt for renewable energy sources.

- As the tax level rises, the demand rate faced by the incumbent utility decreases. The additional cost from the increasing tax level forces consumers to switch to renewable energy sources.

The changes to the demands rate induced by the changes in the tax level, shows that taxes can be used successfully to influence the penetration of renewable energy utilities into the electricity markets in developing economies. Another analysis of interest is how the prices change with network size, N_d. The following derivatives are derived with respect to N_d;

$$\frac{\partial p_d}{\partial N_d} = \frac{2\theta_e \theta_d c_d [N_d - 1]}{4\theta_e \theta_d - \beta_e \beta_d} > 0 \tag{5.23}$$

$$\frac{\partial p_e}{\partial N_d} = \frac{2\beta_e \theta_d c_d [N_d - 1])}{4\theta_e \theta_d - \beta_e \beta_d} > 0 \tag{5.24}$$

The equations (15) and (16) show that ;

- The price of the incumbent increases as the demand or network size increases. This is expected from the general inverse demand function of price and demand.

- The price of the entrant increases as the demand or network size of the incumbent increases. An increase in the p_d causes an increase in the demand rate for the renewable energy source. This implies that demand for renewable energy is increasing, and from the inverse demand function, p_e should increase.

- $\frac{\partial p_d}{\partial N_d} > \frac{\partial p_e}{\partial N_d}$, the rate of increase of the incumbent utility is greater than that of the entrant utility. Even though the two are perfect substitutes, there are other factors such as consumers knowledge about the impact of fossil fuel, accessibility of renewable energy that can make the increase in price of the entrant utility less than that of the incumbent.

The remarks above show the consistent of the models proposed with economic theory of demand and prices. It follows that; $\frac{\partial p_d}{\partial c_e^0} > 0$, $\frac{\partial p_d}{\partial c_d^0} > 0$, $\frac{\partial p_e}{\partial c_e^0} > 0$, $\frac{\partial p_e}{\partial c_d^0} > 0$.

From the above equation(18) we have ;

$$\frac{\partial \psi_d^*}{\partial z_e} = \frac{-\beta_e \theta_e \theta_d}{(2\theta_d \theta_e - \beta_e \beta_d)(c + c\theta_d)} < 0^1 \tag{5.25}$$

$$\frac{\partial \psi_d^*}{\partial z_d} = \frac{1}{c + c\theta_d} > 0 \tag{5.26}$$

$$\frac{\partial \psi_d^*}{\partial c_d^0} = \frac{-\theta_d}{1 + \theta_d} < 0 \tag{5.27}$$

$$\frac{\partial \psi_d^*}{\partial c_e^0} = \frac{\beta_d \theta_e \theta_d}{(2\theta_d \theta_e - \beta_e \beta_d)(1 + \theta_d)} < 0 \tag{5.28}$$

Equations (25-28) implies the following ;

- If the cost of the renewable sources to the society,z_e increases , the tax level applied to the conventional fuel sources decreases. This is in line with the objective of the policy maker since the goal is to cut competitive disadvantages for sources that help minimize the social cost. A higher ,z_e, implies an increase in the social cost due to the generation of electricity from renewable sources. Since there are no emission from renewable source, the increase in social cost can come from the vast amount of land required by some of the renewable technologies e.g solar energy generation.

- If the unit cost of the conventional fuel energy generation to society,z_d increases, the tax level applied to the conventional fuel sources increases. This is meant to efficiently reduce demand.

- If the conventional energy sources have a higher initial cost, c_d^0, then the optimal tax level is reduced. The higher initial cost of the conventional energy sources implies that there is minimal cost advantage between the two firms.

[1] We have $\frac{\partial \psi_d^*}{\partial z_e} < 0$ since $(2\theta_d \theta_e - \beta_e \beta_d) > 0$ and all the parameters are greater than zero.

- A higher initial cost of the renewable energy source,c_e^0, implies an increased cost disadvantage of the entrant firm to the incumbent. This results in higher tax level on the incumbent in order to leverage this cost gap.

5.6 Conclusions

It is important for policymakers to use economic instruments to control negative externalities. It is especially important in the case where climate friendly technologies are more expensive to adopt compared to the conventional and existing technologies. This study focused on electricity markets in developing that are dominated by conventional energy sources and a need to leverage the competitiveness of firms providing energy from renewable sources. Using a duopoly market; there are two levels of strategic interactions introduced; the pricing competition between the market players and the optimal tax level introduced by the policymaker. This project showed that introducing a tax on the price of the conventional fuel allowed the entrant utility to be competitive in terms of marked prices. A tax policy relieves the government of the financial burden of subsidizing renewable energy utilities. The analytical solutions presented in this project highlights the policy adjustments that can be made when the parameters change. The general form of the model allows policy makers in different economies to use country specific parameter levels in order to inform policy decisions. This model can be extended to multiple players in the market.

Chapter 6

Measuring the effects of Competition and Privatization in Electricity Markets: An Econometric Approach

6.1 Introduction

The restructuring of electricity markets have been in effect over the past four decades with Chile being one of the first countries to begin the restructuring process. The main objective of restructuring electricity markets is to achieve economic efficiency. This objective is to be realized through the introduction of private capital, the liberalization of the market which allows competition to exist, and the introduction of independent regulatory institutions to monitor the market players [96]. It is important for the policy maker to establish the privatization model to implement, the timing and the sequencing of the privatization process. This is especially important since it affects the levels of economic growth due to the privatization process [97]. The nature of ownership of firms in a market and the degree of competition are both important factors that influences the price of goods, the cost of production and the output levels. In the case of electricity markets, it determines the advances in technologies to be used, and the generation of output. When implemented efficiently, the confluence of privatization, competition and improved regulatory framework should lead to improved economic performance. In the presence of weak institutions the benefits of competition and privatization might not be fully realized. A lot of developing countries have weaker institutions, therefore there is a need to quantify the economic effects of privatization in order to understand how privatization affects the economy of these countries. Econometric methods have been used to measure the effects of privatization on service penetration, capacity expansion, labor efficiency and prices to consumers.

Liberalization of electricity markets is already at an advanced stage or has been completed in American, European and some Latin American countries. Some countries in the Middle East and the majority of Sub-Saharan Africa are still in the early stages of implementing liberalization reforms. The African electricity market has faced under-investment over a long period of time due to under pricing and other contributing factors. This is due to the fact that the majority of the utilities companies in developing countries are state owned monopolies. The weak institutional structures in developing countries and political incentives for standing governments exacerbate the under pricing problem. The lack of investments directly leads to poor performance of the electricity industries in developing countries [98]. Since Sub-Saharan Africa has not yet liberalized, it is important to understand the impacts of these effects in this study.

Can the economic effects of privatization be empirically measured? This question has been part of recent research on the privatization of firms. The majority of research focuses on the improvements in efficiency levels as a measure of the effects of privatization. The efficiency measures used include but are not limited to productivity, employment and profits. The effects of privatization on the efficiency measures in electricity markets is a well researched topic and some of the findings are given in detail in the literature review. Besides the benefits of improved efficiency levels; Is it possible to measure the economic benefits of privatization from the consumers perspective? This paper addresses this question in detail.

The economic benefits of privatization from the consumer's perspective can be analyzed in terms of consumer welfare. However, due to the difficulty in precisely determining the welfare change, it is difficult to measure the welfare effect of privatization on the poor [115]. Even though it is difficult to measure the welfare effect of competition and privatization,an econometric effect of competition and privatization can be quantified. This calls for indirect measures of improvement in welfare; increased access to electricity and lower tariffs can be used as measures of indirect improvements in welfare. Electricity access is regarded as an important indicator of economic growth. Improved access to electricity improves social welfare by improving access to clean water, education, improved health, access to television and increased income. This study uses electricity access as a measure of the effects of privatization and competition in electricity markets. This can inform government policy on the best economic approach to the question of liberalizing the electricity markets in developing economies. The status quo of public utilities being the only utility providers does not provide for competition. The lack of competition leads to inflated connection fees. The inflated connection tariffs can force poor households to seek alternative sources of power e.g paraffin and wood. These sources of fuels can turn out to be more costly compared to the cost of electricity from the public utility [114].

This paper uses an econometric approach similar to the one in [117], to analyze the effects of competition and regulation of the electricity markets in developing economies as measured by the price of household electricity, access to electricity and system losses. This study extend on [117], by investigating regional effects. This study also analyzes economic regional effects on performance measures to provide comparison between economic regions. This is especially important for policy makers in Sub-Saharan Africa where an estimated 600 million people do no have access to electricity and these account for 60% of the world population without electricity. This study will provide a quantitative benchmark for policy makers in less developed economic regions and instruments that can improve the access to electricity in less developed economies.

6.2 Literature Review

There are a number of research articles that have looked at the impact of the nature of firm ownership and the presence or lack of competition using different metrics. Some of the metrics used to measure this effect include, employment, total factor productivity, cost of production, profits and prices. The findings from these studies have not been consistent thus making it difficult to understand the effects of market structure on consumer welfare.

The main contribution of these studies is that the effects of privatization, competition and regulation should be analyzed to understand the individual and interactive effects on the performance metrics. A lot of studies that focus on measuring the effects of privatization focus on developed countries [96], and while there have been an increasing number of studies on developing countries they have been mostly focused on Latin American countries. There is an opportunity to expand to this growing literature by focusing on Sub-Saharan countries only and a mixture of both Sub Saharan countries and Latin American countries.

A study using a fixed effects model during the 1986-1995 time period found that privatization is positively correlated with the main lines per employee and growth in main lines per employee. However, the study also concludes that competition does not affect network expansion but it directly affects efficiency when measured in main lines per employee [99]. A study on the Argentinian railway industry on the effects of privatization showed a 370 % increase in labor productivity due to privatization [100]. Using panel data to analyze the performance of power sectors supported by the World Bank loans, the analysis showed that the countries that had undergone privatization had significantly higher efficiency compared to the ones still to implement privatization [101]. Using panel data for both developed and developing economies, there is empirical evidence that privatization leads to economic gains measured by profits, productivity and employment [102].

A number of studies that used panel data to analyze the effects of privatization on the economies of developing countries found evidence of performance gains, as defined by productivity, labor and firm performance, in developing countries/economies [103, 104, 105, 106, 96].

There exist studies that have shown the need to be cautious about the economic gains from the privatization of utilities. The investigation on the privatization of electricity generation in 38 developing and developed economies showed that privatization on its own might not lead to economic gains, but effective regulation plays a pivotal role in the success of privatization [107]. The importance of effective regulation is also emphasized in [108]. Two separate studies show that there is a highly unequal asset and income distribution in Latin America which is directly associated with the privatization [109, 110]. This suggests that privatization alone does not lead to an overall improvement in welfare of the population, instead it can create a highly unequal economic environment. In some cases there is no evidence that privatization improves economic gains; an investigation using electricity production as a measure of performance found that publicly owned firms performed as well as the privately owned ones [101].

The existence of mixed results of the effects of privatization on economic gains can be interpreted as a sign of the existence of omitted variables that can explain economic gains. These variables/factors that can be taken into account include the type of market competition, the functions of institutions, the stage of development for capital markets and property rights [111, 112, 113]

Using the data from Chilean telephony system and electricity system to measure the welfare effect of having privatized public utilities; one study showed a gain in consumer surplus in privatized systems that are well regulated. The study estimates the consumer welfare gain to be US$ 2.3 billion from privatizing the telephony system, while the consumer welfare gain for privatizing the Chlgener electricity entity was US$ 18.2 million [116]. The study also shows there is a significant difference between the welfare gain due to privatization in a system that is well regulated compared to a system without regulation [116]. This shows that the benefits of regulation significantly outweighs the costs of implementing regulation.

The majority of literature measures the effects of privatization and competition on the performance of the firm. This study is fundamentally focused on capturing the effects of changing the electricity markets, from the traditional monopolistic design to liberalized markets, on economic development indicators. Access to electricity is one of the known determinants of economic growth. Even though total access to electricity is not a sufficient condition for poverty eradication, it is regarded as a necessary condition for poverty eradication [120]. In this study this idea is extended to the performance of the firm in improving the welfare of the population. Access to electricity plays a pivotal role in eradicating poverty, improving the health and well being of the population, improved access to clean drinking water [119]. Having access to electricity improves household financial health by reducing expenditures on kerosene, charcoal or mobile phone charging costs. This provides households with better health, education, communication and leads to an increase in income levels of the household [118]. If the improved access to electricity is a product of renewable energy sources, this can lead to reduction in carbon dioxide emissions by as much as 330 million metric tons [118]. While it is important to focus on the firm level improvements in productivity and profits, measuring the direct effects of the changes in the market on the general population will lead to socially driven policies that improves the welfare of consumers. While this approach might confound some of the effects of introducing privatization and competition, it provides a quantitative measure to policy makers with interests in maximizing social welfare while creating a liberalized market. In order to cater to the policy maker interested in both social welfare and firm efficiency; this paper also measures the effects of privatization and competition on system losses and price of electricity.

6.3 Research Hypothesis

6.3.1 Privatization

Privatization of the electricity markets changes the incentive structure of the players in this market. Privatization eliminates government interference in the operations of the player therefore reducing political and special interest groups influence the management of the utility.
P1 *Privatization of the electricity markets leads to an increase in electricity access.*
P2 *Privatization of the electricity markets leads to an decrease in system losses.*

6.3.2 Competition

In economic theory, competition provides a path to achieve allocative and technical efficiency. In electricity markets technical efficiency leads to lower system losses, capacity increments and ultimately lower prices. The increase in capacity and lower prices should lead to a reduction in theft. This is under the assumption that the majority of theft of electricity in developing economies is driven by the inability to afford the current electricity tariffs. The new regime of low prices and the increase in new consumers leads to an increase in electricity demand. In order to meet this new demand level, an increase in output levels is required.
P3 *Competition in electricity markets leads to an increase in electricity access.*
P4 *Competition in electricity markets leads to an decrease in system losses.*

6.3.3 Performance Measures

The performance of electric utilities is important in evaluating the reform of electricity markets in different economies. The World Bank is a leader in defining the performance metrics that can be set for quantitative and qualitative evaluation of electric utilities. The World Bank introduced the Electric Utility Capacity Assistance Program (EUCAP) for Africa whose aim is to collate relevant utility performance data within the context of the Bank operations [121]. This program created objective benchmarkers for key performances indices (KPI). This work achieves the multi objective criteria of the Bank to assess the utilities and to motivate them to provide better services. These measures are divided into three categories;

- Technical
- Commercial
- Operational Capabilities

6.3.4 Technical : System Losses

System losses have been consistently used as a performance indicator. System losses monitoring is important due to the insight it provides on the performance of multiple financial and commercial areas of the electricity market. The total system losses measure all the energy losses that occur during the process of transmission and distribution of electricity from the generation source to the consumers of electricity. System losses are measured as the difference between the power generated by the supplier and the power accounted for by the consumer bills. The system losses accounts for market failures and technical losses. Systems losses are expressed as;

$$\textit{System losses} = \frac{\textit{Net Supply - Net Demand}}{NetSupply} \tag{6.1}$$

System losses mostly consist of technical losses e.g. magnetic losses, heat losses and transformation losses an non-technical losses e.g. fraud(tampering, bypasses) and meter failures. Since it is difficult to have a precise measure of technical losses and non-technical losses, the system losses provide a better performance measure for comparative purposes than technical losses and non-technical losses as separate measure.

The total system losses are represented as a percentage of the total supply of electricity in a given system or network. Therefore, it can also be shown in terms of the energy i.e GWH. Recording or measuring system losses is especially important for developing economies since it is a good measure of the overall performance of the market players in terms of the energy they generate and the revenue or billable energy to the consumers. A reduction in system losses leads to improvement in financial performances of the utility. Policy makers and the government have interests in this performance measure as it has immediate implications on the tariff levels and policy making for electricity market players.

Using system losses as a performance measure of the utilities in the market is limited to the overall system, and it cannot be used to track the root source of the non-technical inefficiencies in the system. This lack of specificity is one of the limitations of system losses as a performance measure. In developing economies, the majority of the non technical losses can be attributed to theft [122]. Another limitation of this performance measure is confounded in the initial measurement of the system losses; in most cases the system losses reported are an estimate rather than an accurate value due to the measuring faults. Understanding the measuring issues of system losses is beyond the scope of this paper, however it is important to note that they exist.

6.3.5 Household Access to Electricity

One of the most important indicators of economic development is household electricity access. It is measured as a proportion (percentage) of the number of households that are formally connected to the grid or off grid source. This does not include informal consumers of electricity as defined in [122]. The access percentage is calculated as follows;

$$Household\ access\ to\ electricity = \frac{Number\ of\ households\ connected\ to\ electricity * 100}{Number\ of\ households\ in\ the\ country} \quad (6.2)$$

Access to electricity is an important indicator of the electricity market performance. It indirectly captures the level of affordability of electricity and infrastructural development levels to meet developmental goals. One of the main developmental goals for developing economies is to increase the levels of electricity access in specified periods. Since a number of commercial firms in Sub-Saharan Africa operate in housing areas, the level of household electricity access is a suitable proxy for measuring commercial access to electricity [121]. For this study, there are two performance measures that will be measured under household access to electricity namely; Urban Access to electricity and Rural Access to electricity. These two measures are separated as they capture different aspects of the electricity markets. It is expected that there is some positive correlation between these two measures as they both capture some variation in the changes in economic growth of a country. However some countries adopt specific policies to improve rural electrification while others do not have such a policy. This creates the need to use both measures as performance measures of the electricity market for an individual country. The access to electricity is bounded by [0,100], in order to avoid negative values in the analysis a logistic transform of the variable can be used.

6.4 Data

The data collected for this study covers 1990-2015 period. One of the main reasons for choosing this time range is the fact there was an increased shift to privatization of electricity markets in the early 1990s. This time frame has readily available data compared to any prior period. An observation is defined as a country-year. The data set is a panel data. However, in this case, not all countries have observations or the full time frame. Therefore the data set used for this study is an unbalanced panel data. The unbalanced panel data can be used to explore the quantitative effects of privatization, competition and liberalization on the electricity markets. In this study, the measures of interest are; system losses, price and access to electricity.

The data set includes the performance measures ($perf_{it}$) and the control variables (X_{it}). The control variables are chosen to pick up specific economic features of each individual country and the specific features of the electricity market for each country. The control variables chosen indicates the performance of each countries electricity market performance ; the variables that controls for this country specific factor are Energy Imports, Consumption per capita e.t.c. They also highlight the underlying policy structures on rural electrification and development as highlighted by electricity from IPPs, renewable energy as a percentage of consumption. The control variables also need to explain the different economic statuses of each country ; the variables that control for this include CPI, Short Term Debt and GDP. Table.1 is a summary of the definitions of the variables used in the study ;

Table 6.1: Variable Definitions

Variable Name	**Unit**	**Definition**
Privatization Status	binary	This is a binary variable whether the incumbent utility is privatized or it is publicly owned. In this case 0 =the incumbent is publicly owned and 1 = the incumbent is privately owned.
Monopoly status	binary	This a country specific binary variable for the existence of a monopoly in the electricity market or the availability of competition.
Perfomance Measures		
Price(Tariffs)	$ MWh	the average yearly tariffs for a MWh of electricity energy.
Access national	%	The percent of the national population with access to electricity.
Access Urban	%	The percent of the urban population with access to electricity.
Access Rural	%	The percent of the rural population with access to electricity.
Control Variables		
GDP	$	Gross Domestic Product Index
CPI	ratio	Consumer Price Index
Electricity from IPPs	MWh	Energy produced or purchased from IPPs
Energy Imports	MWh	Energy that is bought from other nations
Consumption per Capita	ratio	The ratio of energy consumed to the total population
Renewable Energy	%	The percentage of total energy from renewable sources.
Short term Debt	ratio	The ratio of short term debt to GDP
Long term Debt	ratio	The ratio of long term debt to GDP

Table 6.2 is a summary statistics for the data used in this study;

Table 6.2: Descriptive statistics

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Energy Imports	910	0.6	91.1	−426.8	−22.0	57.4	90.9
% Rural Access	910	71.6	35.0	0.3	39.0	100.0	100.0
% Urban Access	910	91.3	15.9	24	89.0	100	100
% National Access	910	81.0	27.2	5.5	65.1	100.0	100.0
% Renewable Energy	910	39.9	32.0	0.04	10.1	66.9	100.0
Consumption per Capita	910	13.2	7.1	1.5	7.9	17.1	46.6
System Loss	910	13.2	7.1	1.5	7.9	17.1	46.6
CPI	910	71.1	32.9	0.001	47.4	97.0	214.7
Short term Debt	910	9.3	10.1	0.0	0.0	14.8	79.8
Income per Capita	910	7,231.4	10,702.8	68.5	1,106.5	7,949.1	53,696.2
% Urban Population	910	59.2	17.6	17.6	45.7	69.9	97.8
Long term Debt	910	0.03	0.04	0.0	0.0	0.1	0.3

6.5 Methodology

The data used in this study is collected over a period of 25 years, 1990-2015. The assumption is that the performance measures for the electric utilities depends on other explanatory variables which might not be observable but influences the performance measures. This data has both time varying and time invariant predictors. This is the reason why we employ a fixed effect estimator. The response variables which are the electric utility performance measures are time varying. Analyzing this data can lead to non-observed cross sectional heterogeneity. In order to minimize the confounding error, this study uses a fixed effects model approach to analyze the changes in the performance measures over time. The fixed effects approach that focuses on within country changes helps in eliminate time-invariant sources of heterogeneity. In this study the fixed effect model is a viable tool for analysis as it controls for the unobserved time invariant country specific factors. The countries in this study are from four economic regions, namely Latin America and Caribbean,Sub-Saharan Africa,Europe,and Middle East and North Africa. Even though there are four distinct economic regions, each country has specific economic conditions that the fixed effects model can capture. The initial analyses is done by estimating the following equations;

$$perf_{it} = \alpha_i + \gamma_t + \beta_1(Priv_{it}) + \theta(X_{it}) + \varepsilon_{it} \tag{3a}$$

$$perf_{it} = \alpha_i + \gamma_t + \beta_1(Mono_{it}) + \theta(X_{it}) + \varepsilon_{it} \tag{3b}$$

Where $perf_{it}$ is the performance measure of interest, $Priv_{it}$ is a binary variable indicating whether the largest utility is private or publicly owned, $Mono_{it}$ is a binary variable indicating the existence of a monopoly or competitive market and X_{it} are the country specific controls described in the previous section.

As stand alone explanatory variable, the privatization binary variable and the Monopoly binary variables might not be able to capture the effects of both competition and privatization of firms.Inorder to account fo this, interactions can be introduced between the binary variables and or some of the controls. This leads to the following formulation of the analysis;

$$perf_{it} = \alpha_i + \gamma_t + \beta_1(Priv_{it}) + \beta_2(Mono_{it}) + \theta(X_{it}) + \varepsilon_{it} \tag{4a}$$

$$perf_{it} = \alpha_i + \gamma_t + \beta_1(Priv_{it}) + \beta_2(Mono_{it}) + \beta_3(Priv_{it} * Mono_{it}) + \theta(X_{it}) + \varepsilon_{it} \tag{4b}$$

The equation above allows the separate exploration of the effects of privatization and competition while also exploring the combined effects of both privatization and competition. This allows us to determine if there is an interactive effect and the meaning of such an interaction in the analysis. Privatization and competition are especially interesting to developing economies as they represent a separation from the government and political influence. In other words, it is an important step towards achieving a free market.

The analysis carried out in this paper has its own pitfalls such as endogeneity. Endogeneity arises in the following cases;

- If there exists an omitted variable that is highly correlated with the regressors.
- if it is the case that the dependent variable and at least one of the explanatory variables are determined simultaneously in the system.
- If there is measurement error in one of the explanatory variables.

How can endogeneity arise in the model discussed in this paper? One of the main issues with developing economies is the collection of accurate data. One study summarizes the causes of collection of poor data as internal and external; the internal reasons being the lack of institutional setup and weak infrastructure while the external one include but are not limited to low literacy rates and lack of awareness in terms of quality data collection [123]. Another cause of endogeneity arises from the fact that poor performance can force the government to form policies to improve the performance of utilities. In this case one of the policy changes can be liberalizing the electricity markets. Liberalization of the markets leads to the privatization of the utilities and allows competitive markets. It can also be the case that privatization or competition leads to the change in the performances of the utilities. This implies that the unobserved influences on the policy reforms may also affect the performance measures of the utilities. Country fixed effects control for a country-specific propensity to liberalized electricity market, while year fixed effects control for general trends of changes in electricity markets.

6.6 Results

The results for estimating the two models proposed above are presented in this section. Both models are estimated for urban population access to electricity, rural population access to electricity and losses due to technical and distribution losses. The results presented here are from unbalanced panel data as some countries have some missing data. The estimation of the models was done in **R** using the *plm* function and controlling for time effects. The code used for data extraction and analysis will be presented in the Appendix section. In general the estimated models show that privatization improves the performance of electricity utilities as measured by both access and technical losses while the absence of competition has the opposite effect.

The following subsections show in detail the model estimation for each performance measure.

6.6.1 Urban Population Access to Electricity

From the first hypothesis, Using the model (3a), **Table 6.3** shows that privatization of the incumbent utility improves access to electricity of the urban population by 6 percentage points. The effect of privatization is significant at less that 1% level. The second model(4a) also shows that privatization improves urban access to electricity by 13 %.

From the second hypothesis, Using the model (3b) and in this case with the competition variable ,**Table 6.3** shows that if the incumbent utility is a monopoly, this reduces the access to electricity of the the urban population by 2.5 percentage points. The competition variable is significant at 10 % level. The second model (4) shows that competition is positively correlated with urban access to electricity. The high correlation between the privatization and competition variable reduces the reliability of the interaction model. The high correlation stems from the fact that countries tend to have either a monopoly that is government owned or competitive markets with an incumbent that is privately owned.

The control variables also presents an opportunity to look at the effects of some of the country specific attributes on the changes in access to electricity in urban areas. Using **Table 6.3** and the model (3a), a country in Sub-Saharan Africa sees a decline of 20 percentage points in urban electricity access. This is consistent with what one would expect given that Sub-Saharan Africa is one of the poorest economic regions in the world. The coefficient of Sub-Saharan Africa is highly significant at 99.99 percent level. The results also show that an increase in urban population increases the levels of access. A rise in urban population can be correlated with economic growth, this implies that as the economy grows, the urban areas increase in size and this increase in size is met with increase in economic opportunities. Energy imports are negatively correlated with urban access to electricity. Importing energy from other countries can result in an increase in domestic tariffs,and often times the increase in tariffs is not met with an increase in income therefore this leads to a reduction in the consumers that can afford formal access to electricity in the urban ares. Access to electricity is positively correlated with the log(Income per capita), as the income of the general populace increases, the number of people that can afford formal access to electricity increases, therefore resulting in an increase in the access levels to electricity in the urban areas. This is consistent with other economic analyses on access to electricity that shows that electricity access is strongly correlated with incomes at both household and national levels . Urban access to electricity is positively correlated with consumption of electricity per capita. The increase in demand of electricity can be partly explained by an increase in household electricity demand, and this increase in demand is largely observed in urban areas. Renewable energy consumption is negatively correlated with urban access to electricity. The high investments cost for renewable energy generation makes renewable energy highly unaffordable [122], therefore an increased adoption of renewable energy on the grid can result in higher tariffs resulting in a decrease in consumers that can afford formal connection to the grid. The correlations discussed in this section are all significant at the 95 percent level or higher.

Table 6.3: Urban Population Access

	Dependent variable:			
	Urb_perc			
	(3a)	(3b)	(4a)	(4b)
Priv1	6.348***		13.883***	13.883***
	(1.147)		(1.938)	(1.938)
Mono1		−2.492*	11.780***	11.780***
		(1.477)	(2.457)	(2.457)
CPI	0.048**	0.048*	0.018	0.018
	(0.024)	(0.025)	(0.024)	(0.024)
Renew_perc	−0.061***	−0.054***	−0.059***	−0.059***
	(0.013)	(0.013)	(0.013)	(0.013)
Urb_Pop_Perc	0.140***	0.146***	0.110***	0.110***
	(0.039)	(0.040)	(0.039)	(0.039)
Cons_Capita	0.098*	0.102*	0.110**	0.110**
	(0.055)	(0.055)	(0.054)	(0.054)
log(Income_per_Capita)	1.841***	1.759***	2.384***	2.384***
	(0.636)	(0.650)	(0.639)	(0.639)
Short_term_Debt	0.146***	0.134***	0.136***	0.136***
	(0.043)	(0.044)	(0.042)	(0.042)
Ener_Impo	−0.010**	−0.012***	−0.013***	−0.013***
	(0.004)	(0.005)	(0.004)	(0.004)
regionLatin America and Caribbe	0.817	0.052	0.313	0.313
	(1.330)	(1.354)	(1.318)	(1.318)
regionMiddle East and North Africa	1.635	0.210	0.236	0.236
	(1.623)	(1.674)	(1.630)	(1.630)
regionSub-Saharan Africa	−17.797***	−20.895***	−22.988***	−22.988***
	(1.849)	(2.161)	(2.124)	(2.124)
Observations	951	951	951	951
R^2	0.643	0.633	0.652	0.652
Adjusted R^2	0.630	0.619	0.639	0.639
F Statistic	150.136*** (df = 11; 915)	143.288*** (df = 11; 915)	142.849*** (df = 12; 914)	142.849*** (df = 12; 914)
Note:				*p<0.1; **p<0.05; ***p<0.01

6.6.2 Rural Population Access to Electricity

From the first hypothesis, Using model (3a), **Table 6.4** shows that privatization of the incumbent utility improves the access to electricity of the rural population by 3 percentage points. The effect of privatization is significant at the 10 percent level. The second model which has the interaction between privatization and competition shows that privatization effect on rural access to electricity is not significant. As mentioned in the previous section, the high correlation between the competition variable and the privatization variable makes the second model less reliable.

From the second hypothesis, Using model (3b) and in this case with the competition variable, **Table 6.4** shows that if the incumbent utility is a monopoly, this reduces the access to electricity of the rural population by 2 percentage points. The competition variable is significant at 95 percent level. The negative correlation in the presence of a monopoly is consistent with economic theory on the disadvantages of a monopoly. A country in Sub-Saharan Africa sees a decline of 45 percentage points in rural electricity access, this is the largest amongst all the economic region. A country in Latin America on average faces a decline of 8 percent in access to rural electricity. Latin America and Sub Saharan Africa house some of the least developed countries and this is highlighted by the low levels of rural access to electricity in both regions. There is a negative correlation with CPI; as the cost of living increases as indicated by the CPI there is a heavier burden on the rural consumer's whose levels of income are low in comparison to the urban population. Also, the rural economy depend on remittances from the urban population, if the cost of living is rising there is a decline in disposable income therefore reducing the income of the rural population. The other variables like, Income per Capita, Energy Imports, CPI , Renewable Energy, have correlations that are consistent with the correlations with urban access to electricity.

Table 6.4: Rural Population Access

	Dependent variable:			
	Rural_perc			
	(3a)	(3b)	(4a)	(4b)
Priv1	3.555**		0.033	0.033
	(1.691)		(2.886)	(2.886)
Mono1		−5.532***	−5.499	−5.499
		(2.138)	(3.653)	(3.653)
CPI	−0.202***	−0.188***	−0.188***	−0.188***
	(0.035)	(0.036)	(0.036)	(0.036)
Renew_perc	−0.115***	−0.116***	−0.116***	−0.116***
	(0.019)	(0.019)	(0.019)	(0.019)
Urb_Pop_Perc	−0.126**	−0.112*	−0.112*	−0.112*
	(0.058)	(0.058)	(0.059)	(0.059)
Cons_Capita	0.170**	0.165**	0.165**	0.165**
	(0.081)	(0.081)	(0.081)	(0.081)
log(Income_per_Capita)	14.436***	14.180***	14.181***	14.181***
	(0.937)	(0.942)	(0.952)	(0.952)
Ener_Impo	−0.024***	−0.023***	−0.023***	−0.023***
	(0.007)	(0.007)	(0.007)	(0.007)
Short_term_Debt	0.234***	0.238***	0.238***	0.238***
	(0.063)	(0.063)	(0.063)	(0.063)
regionLatin America and Caribbe	−7.414***	−7.185***	−7.184***	−7.184***
	(1.960)	(1.963)	(1.965)	(1.965)
regionMiddle East and North Africa	0.856	1.506	1.506	1.506
	(2.387)	(2.423)	(2.424)	(2.424)
regionSub-Saharan Africa	−41.086***	−38.661***	−38.666***	−38.666***
	(2.721)	(3.127)	(3.158)	(3.158)
Observations	941	941	941	941
R^2	0.794	0.795	0.795	0.795
Adjusted R^2	0.786	0.787	0.787	0.787
F Statistic	317.741*** (df = 11; 905)	318.744*** (df = 11; 905)	291.859*** (df = 12; 904)	291.859*** (df = 12; 904)
Note:				*p<0.1; **p<0.05; ***p<0.01

6.6.3 System Losses

From **Table 6.5** we reject the hypotheses that both privatization and competition reduces the system losses on the electricity grid. This is because the coefficients for competition and privatization are not statistically significant. Even though we reject the hypotheses for system losses, the models provide insights on other factors that influences system losses on the electricity grid. Using the first model with either privatization or competition variable, the insights derived from this model is useful in deriving policies that help minimize system losses. Urban population is positively correlated with system losses; as the population in urban areas increases, there is an increase in demand. In order to meet this demand utilities have to produce more energy. If there are no changes in the grid structure the distribution and transmission of more energy results in higher system losses. Renewable energy is negatively correlated to system losses; renewable sources requires the improvement of the electric grid or results in the creation of mini grids, these two factors help reduce the system losses on the grid. Income per Capita is negatively correlated with system losses; this variable can be used as a measure of prosperity, therefore as the prosperity of a country increases their system losses decreases. A prosperous nation can invest in improvements of the electric grid therefore minimizing system losses. It should be noted that there are weaknesses in using income per capita as a measure of prosperity, however, this assumption is sufficient for the purposes of this study. Energy imports are negatively correlated with system losses; as the imports increases the exports decreases, this reduces the losses incurred during transmission and distribution as the losses due to imports are accounted for by the exporting country. This analyses also shows that the economic region of a country matters in accounting for system losses, as show by both tables, countries in Sub-Saharan Africa have the highest system losses while European countries have the lowest system losses; the differences in economic development is captured by this variable. The highly developed regions can afford better infrastructure that results in reduced system losses while developing region like Sub-Saharan Africa face a huge infrastructure deficiency which leads to increased system losses. Policy makers in these regions should recognize the urgent need for developing infrastructures for efficient distribution of electricity.

Table 6.5: System Losses Results

	Dependent variable:			
	Syst_Loss			
	(1)	(2)	(3)	(4)
Priv1	0.258		−1.363	−1.363
	(0.703)		(1.228)	(1.228)
Mono1		−1.071	−2.467	−2.467
		(0.877)	(1.533)	(1.533)
CPI	0.003	0.006	0.008	0.008
	(0.015)	(0.015)	(0.015)	(0.015)
Renew_perc	−0.018**	−0.019**	−0.019**	−0.019**
	(0.008)	(0.008)	(0.008)	(0.008)
Urb_Pop_Perc	0.051**	0.053**	0.055**	0.055**
	(0.024)	(0.024)	(0.024)	(0.024)
Urb_perc	0.031	0.033	0.040	0.040
	(0.025)	(0.024)	(0.025)	(0.025)
Rural_perc	0.017	0.015	0.012	0.012
	(0.016)	(0.016)	(0.017)	(0.017)
log(Income_per_Capita)	−3.666***	−3.692***	−3.720***	−3.720***
	(0.422)	(0.423)	(0.423)	(0.423)
Ener_Impo	−0.015***	−0.014***	−0.014***	−0.014***
	(0.003)	(0.003)	(0.003)	(0.003)
Short_term_Debt	0.076***	0.078***	0.078***	0.078***
	(0.026)	(0.026)	(0.026)	(0.026)
regionLatin America and Caribbe	0.056	0.169	0.120	0.120
	(0.812)	(0.811)	(0.812)	(0.812)
regionMiddle East and North Africa	−3.988***	−3.699***	−3.693***	−3.693***
	(0.968)	(0.984)	(0.984)	(0.984)
regionSub-Saharan Africa	0.691	1.502	1.756	1.756
	(1.247)	(1.392)	(1.411)	(1.411)
Observations	941	941	941	941
R^2	0.293	0.294	0.295	0.295
Adjusted R^2	0.265	0.266	0.266	0.266
F Statistic	31.171*** (df = 12; 904)	31.330*** (df = 12; 904)	29.023*** (df = 13; 903)	29.023*** (df = 13; 903)
Note:				*p<0.1; **p<0.05; ***p<0.01

6.6.4 Interaction Effects

In order to understand the effects of privatization and competition on the regional level, we interact these effects with the region variable. The interaction effect gives insight into the differential impact on privatization and competition relative to the reference group. The interaction variables are chosen based on literature and or other factors. A consistent them of this dissertation is understanding electricity markets in developing countries, specifically Sub-Saharan Africa. It follows from this interest that the interaction effect is specified as shown below;

$$perf_{it} = \alpha_i + \gamma_t + \beta_1(Priv_{it}) + \beta_3(Priv_{it} * region) + \theta(X_{it}) + \varepsilon_{it} \quad (7a)$$

An equivalent version of (7a) is created for the competition variable.

However, a consistent theme of this dissertation is to understand there is a stronger interest on the effects of privatization and competition in Sub-Saharan Africa. In order to further analyze the interaction effects on this region, the following model is created;

$$perf_{it} = \alpha_i + \gamma_t + \beta_1(Priv_{it}) + \beta_3(Priv_{it} * region = SSA) + \beta_4(Priv_{it} * region)\theta(X_{it}) + \varepsilon_{it} \quad (7b)$$

The interaction effect provides information on the effect of privatization and competition based on the geographical region of the country. Controlling for the interaction effect is to modulate the effects of geographical location. From (7a) and Table 6, privatization increases urban access to electricity in Sub Saharan Africa and Europe by 14 %, the effects of privatization on urban access to electricity in the Latin America and Middle East region can be understood by combining the regional interaction. For Latin America, this interaction effect, $(\beta_4 * region + beta_1)Priv$,is 5% , while the interaction effect for Middle East is -1%. The privatization effect is not significant for rural access , however the interaction effect for Middle East is significant, resulting in an effect of 16%. The rest of the explanatory factors have similar explanations as already given in the sections above.

In order to understand the interaction effect on Sub Saharan Africa, model (7b) which makes the region equal to Sub-Saharan Africa is used. From this model the interaction effect is given by , $(\beta_3 * region + beta_1) * Priv$, which is 14% for urban access , this is consistent with model (7a). For rural access, the privatization interaction has -1% on access in rural populations. The results in **Table 7.6** and **Table 7.7** shows that model (7a) and (7b) are equivalent. The general insight emerging from the interaction effects analysis is that privatization and competition have a strong impact in Sub-Saharan Africa and the Middle East. Intuitively, both regions have the lowest levels privatization of utilities and lower access rates to electricity. Introducing privatization in these markets should analytically improve the levels of access. Another interpretation of these findings is that since Sub Saharan Africa has lower privatization and competition levels, its electricity markets are not economically efficient and one consequence of this is reflected in the lower levels of electricity access in this region. This also provides a policy change opportunity in the poor performing regions. Creating policies that encourage privatization and competition in Sub-Saharan Africa should be a priority to policy makers in this region.

The analysis for privatization effects can be repeated for the competition effects, the summary of this analysis is shown in **Table 7.8**

Table 6.6: Region* Privatization Interaction

	Dependent variable:		
	Urb_perc	Rural_perc	Syst_Loss
	(1)	(2)	(3)
Priv1	14.051***	−0.863	−1.655
	(1.920)	(2.835)	(1.220)
CPI	0.006	−0.152***	0.015
	(0.025)	(0.037)	(0.015)
Renew_perc	−0.060***	−0.111***	−0.018**
	(0.013)	(0.019)	(0.008)
Urb_Pop_Perc	0.104***	−0.087	0.058**
	(0.040)	(0.059)	(0.024)
Cons_Capita	0.119**	0.132	
	(0.054)	(0.081)	
Urb_perc			0.053**
			(0.026)
Rural_perc			0.001
			(0.017)
log(Income_per_Capita)	2.706***	13.021***	−3.871***
	(0.661)	(0.977)	(0.425)
Ener_Impo	−0.016***	−0.010	−0.011***
	(0.005)	(0.007)	(0.003)
Short_term_Debt	0.141***	0.224***	0.074***
	(0.042)	(0.062)	(0.026)
regionLatin America and Caribbe	10.120***	−5.906	−0.651
	(2.904)	(4.284)	(1.792)
regionMiddle East and North Africa	14.189***	−11.691***	−8.214***
	(2.909)	(4.292)	(1.815)
regionSub-Saharan Africa	−10.838***	−45.916***	−1.388
	(2.276)	(3.358)	(1.528)
Priv1:regionLatin America and Caribbe	−9.498***	−2.560	0.352
	(2.788)	(4.109)	(1.705)
Priv1:regionMiddle East and North Africa	−15.271***	17.688***	5.750***
	(3.046)	(4.492)	(1.939)
Observations	951	941	941
R^2	0.654	0.799	0.301
Adjusted R^2	0.640	0.791	0.271
F Statistic	132.604*** (df = 13; 913)	276.497*** (df = 13; 903)	27.696*** (df = 14; 902)
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 6.7: Region* Privatization Interaction with Sub-Saharan Africa Specification

	Dependent variable:		
	Urb_perc	Rural_perc	Syst_Loss
	(1)	(2)	(3)
Priv1	−1.220	16.825***	4.096***
	(2.243)	(3.305)	(1.388)
CPI	0.006	−0.152***	0.015
	(0.025)	(0.037)	(0.015)
Renew_perc	−0.060***	−0.111***	−0.018**
	(0.013)	(0.019)	(0.008)
Urb_Pop_Perc	0.104***	−0.087	0.058**
	(0.040)	(0.059)	(0.024)
Cons_Capita	0.119**	0.132	
	(0.054)	(0.081)	
Urb_perc			0.053**
			(0.026)
Rural_perc			0.001
			(0.017)
log(Income_per_Capita)	2.706***	13.021***	−3.871***
	(0.661)	(0.977)	(0.425)
Ener_Impo	−0.016***	−0.010	−0.011***
	(0.005)	(0.007)	(0.003)
Short_term_Debt	0.141***	0.224***	0.074***
	(0.042)	(0.062)	(0.026)
region == "Sub-Saharan Africa"	−26.109***	−28.228***	4.363**
	(2.651)	(3.907)	(1.694)
regionLatin America and Caribbe	−5.152	11.782**	5.100***
	(3.208)	(4.728)	(1.962)
regionMiddle East and North Africa	−1.083	5.998**	−2.464**
	(1.766)	(2.603)	(1.076)
Priv1:region == "Sub-Saharan Africa"	15.271***	−17.688***	−5.750***
	(3.046)	(4.492)	(1.939)
Priv1:regionLatin America and Caribbe	5.773*	−20.248***	−5.398***
	(3.129)	(4.613)	(1.942)
Observations	951	941	941
R^2	0.654	0.799	0.301
Adjusted R^2	0.640	0.791	0.271
F Statistic	132.604*** (df = 13; 913)	276.497*** (df = 13; 903)	27.696*** (df = 14; 902)
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 6.8: Region* Competition Interaction

	Dependent variable:		
	Urb_perc	Rural_perc	Syst_Loss
	(1)	(2)	(3)
Mono1	0.138	-16.754^{***}	-3.903^{***}
	(2.302)	(3.298)	(1.383)
CPI	0.039	-0.153^{***}	0.012
	(0.025)	(0.036)	(0.015)
Renew_perc	-0.055^{***}	-0.111^{***}	-0.018^{**}
	(0.013)	(0.019)	(0.008)
Urb_Pop_Perc	0.141^{***}	-0.090	0.056^{**}
	(0.040)	(0.058)	(0.024)
Cons_Capita	0.109^{*}	0.133^{*}	
	(0.056)	(0.081)	
Urb_perc			0.043^{*}
			(0.025)
Rural_perc			0.006
			(0.017)
log(Income_per_Capita)	2.013^{***}	13.070^{***}	-3.833^{***}
	(0.673)	(0.967)	(0.425)
Ener_Impo	-0.015^{***}	-0.010	-0.011^{***}
	(0.005)	(0.007)	(0.003)
Short_term_Debt	0.137^{***}	0.224^{***}	0.075^{***}
	(0.044)	(0.062)	(0.026)
region == "Sub-Saharan Africa"	-14.976	-51.519^{***}	0.905
	(11.456)	(16.413)	(6.801)
regionLatin America and Caribbe	0.313	-8.422^{***}	-0.229
	(1.371)	(1.970)	(0.824)
regionMiddle East and North Africa	-0.836	5.980^{**}	-2.533^{**}
	(1.817)	(2.603)	(1.076)
Mono1:region == "Sub-Saharan Africa"	-8.351	23.147	3.006
	(11.629)	(16.661)	(6.885)
Mono1:regionLatin America and Caribbe	-4.621	20.154^{***}	5.143^{***}
	(3.215)	(4.607)	(1.934)
Observations	951	941	941
R^2	0.634	0.799	0.299
Adjusted R^2	0.619	0.791	0.270
F Statistic	121.469^{***} (df = 13; 913)	276.520^{***} (df = 13; 903)	27.510^{***} (df = 14; 902)
Note:			*p<0.1; **p<0.05; ***p<0.01

6.7 Conclusions

This study provides an empirical analysis of the effects of privatization and competition on the performance of electricity markets. Using the linear model, this study shows the effects of privatization and competition on a access to electricity and system losses. While there are limitations to this analysis, it provides a framework for effectively measuring the performances of utilities. This analysis also provides insight on other determinants of performance of electric utilities; this is especially important for policy makers in terms of creating instruments that can improve the performance of electric utilities.This analysis shows that privatization of utilities and the introduction of competition improves the levels of access of electricity amongst the rural and the urban population. However, these two factors do not have a significant effect on system losses. The results show that system losses are directly correlated with the overall prosperity of a country as shown by variables that are directly correlated with system losses. Access to electricity is one of the main indicators of economic growth, and the results show that Sub-Saharan Africa and Latin America, two of the least developed regions, have lower levels of electricity access in comparison to other economic regions. The results show a decrease of 20 percentage points for urban access and 40 percentage decrease in rural access if a country is in Sub-Saharan Africa. These indicators calls for a need in economic reforms for countries in Sub-Saharan Africa in order to increase accessibility of electricity in this region. The regional effects provides a great contrast between regions that have adopted privatization and competition to regions that are still in the process of implementing the two; Europe and Sub-Saharan Africa provides a great example of this contrast. European electricity markets are liberalized and there is both public and private participation on the market, while the Sub-Saharan African markets are heavily dominated by government control with the majority of the markets having one single dominant utility player. A juxtaposition of these two markets shows that markets in developing economies under perform when compared to European markets in terms of access to electricity and system losses. The results presented in this study are consistent with economic theory and other studies on economic development. The analysis presented is an effective way of measuring the performance of electricity markets. The econometric approach provides policy makers with empirical evidence on the policy changes.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The majority of developed countries have made the shift from monopoly designs to competitive markets that allows for higher reliability and improved quality of service. The majority of developing countries, especially in Sub Saharan Africa have a monopoly or semi-deregulated market structure. Most developed countries have on average 100 % electricity access for both the urban and rural populations. Developing countries still lag in the levels of electricity access for both the urban and rural populations, on average the rural populations have a much lower access rate compared to the urban population. This is due to the poor infrastructure distribution level, most of the utility infrastructure is heavily concentrated in urban areas. There are country specific initiatives to improve the infrastructure and access levels, for example, South Africa and Zimbabwe have a rural electrification program that is meant to accelerate infrastructure development to rural parts of the country. The first study presented an inter-temporal framework for analyzing the pricing path that can be employed by a competitive incumbent and a competitive market entrant in the electricity markets of developing economies. It provided a policy framework that is consistent with the policy needs in developing economies i.e encouraging participation of private players in the electricity markets and provided a profitable framework that can be implemented by new investors. This study also provided a robust extension of the theoretical framework introduced by Chisari. Market players employ an increasing pricing path that converge to the steady state prices of competitors.

The calls for a cleaner earth and the advancements in technologies used to extract and use renewable energy sources have changed energy economics. There is a need for an active investigation into how to efficiently reduce the emissions levels from electricity generation in order to minimize environmental damage and increase consumer welfare. These models can vary from place to place depending on consumption levels and energy sources available. Pigouvian taxes and Tradable permits have been used to reduce the emissions of greenhouse gases to efficient levels. This study focused on electricity markets in developing that are dominated by conventional energy sources and a need to leverage the competitiveness of firms providing energy from renewable sources. Using a duopoly market; there are two levels of strategic interactions introduced; the pricing competition between the market players and the optimal tax level introduced by the policymaker. This project showed that introducing a tax on the price of the conventional fuel allowed the entrant utility to be competitive in terms of marked prices.

The focus of the first two studies is on a policy level. However, it is important to measure the effects of these policy changes using some objective benchmarks. This allows the policymaker to evaluate the effects of the old and new policies. A cross country or cross geographical study allows the policy maker to have a comparative view of the performance of their electricity markets relative to other markets in their region or in other regions. This objective measure allows for critical analysis of the policies implemented in individual countries or regions.The last study provides an empirical analysis of the effects of privatization and competition on the performance of electricity markets. Using the linear model, this study shows the effects of privatization and competition on a access to electricity and system losses. While there are limitations to this analysis, it provides a framework for effectively measuring the performances of utilities. This analysis also provides insight on other determinants of performance of electric utilities; this is especially important for policy makers in terms of creating instruments that can improve the performance of electric utilities.

7.2 Future Work

Policy makers in developed and developing economies often regulate the prices of electric utilities. The goal of price regulation is to protect consumers from predatory pricing by utilities. In developing economies where the electricity markets are dominated by monopolies, pricing regulation can protect consumers from monopoly pricing. However certain pricing caps e.g dynamic pricing cap, allows an entry deterring incumbent firm to set its prices such that an potential entrant is not profitable upon entry. Future work will focus on a strategic interaction between an incumbent firm, a policy maker and a potential entrant. The goal is to strategically place the policy maker to minimize entry deterrence on the part of the incumbent by transferring a subsidy to the potential entrant to reduce its entry costs. The model presented in Chapter 4 can be extended to look at the Stackelberg set up, this will allow the incumbent firm to be the leader while the entrant firm is the follower in price setting. This can present interesting insight in the analysis of developing markets. The strategic interaction in Chapter 5 can be expanded to cover the stochastic nature of demand functions. That will provide a detailed analysis for firms to contrast with the deterministic solution. In both chapters numerical examples can add more insight on the pricing strategies provided by the analytical solutions provided. The work presented in this dissertation provides a lot of avenues for further analysis of electricity markets in developing economies.

7.3 Publications

1. Matenga.Z, Fedderke.J and Terpenny.J, 2018, ”Pricing Dynamics of Electricity in Privatized Markets with Underdeveloped Networks” *IISE Conference*

2. Matenga.Z, Fedderke.J and Terpenny.J, 2019, ”Optimal Taxing Strategy to Increase Competitiveness of Green Utility Suppliers: A Theoretical Framework” *Accepted IISE Conference*

3. Matenga.Z, Fedderke.J and Terpenny.J, 2018, ”Pricing Dynamics of Electricity in Privatized Markets with Underdeveloped Networks” *under review Energy Economics*

4. Matenga.Z, Fedderke.J and Terpenny.J, 2019, ”Optimal Taxing Strategy to Increase Competitiveness of Green Utility Suppliers: A Theoretical Framework” *under review Energy Policy*

5. Matenga.Z, Fedderke.J and Terpenny.J, TBD, ”Measuring the effects of Competition and Privatization in Electricity Markets: An Econometric Approach” *to be submitted Energy Policy*

Bibliography

[1] Rothwell.G and Gómez.T, 2003, ”Electricity Economics: Regulation and Deregulation,”*IEEE Power Engineering Society*

[2] Chisari.O and Kessides.I, 2009, ”Pricing Dynamics of Network Utilities in Developing Countries,” *Review of Network Economics*, vol(8)Issue 3.

[3] Buchanan.J and Tullock.G, 1962,”The Calculus of Consent: Logical Foundations of Constitutional Democracy,” *University of Michigan*

[4] Stern.J and Holder.S , 1999, ”Regulatory Governance: Criteria for Assessing the Performance of Regulatory Systems”

[5] Transparency International, 2017, *Corruption Perceptions Index*

[6] World Bank(2008) *Sustainable Infrastructure Action Plan.*

[7] World Energy Council, 2001, *Pricing Energy in Developing Countries.*

[8] Modise.D and Mahotas.V, 2009,”The South African Energy Sector,” *Department of Energy*.

[9] Aschauer D.A, 1989, ”Is Expenditure Productive?”*Journal of Monetary Economics,23:*177-200

[10] Estache.A , 2005, ”What do we know about Sub-Saharan Africa’s Infrastructure and the Impact of the 1990’s Reforms?”*Mimeo,* World Bank, Washington DC.

[11] Leipziger.D , Fay.M, Wodon.Q and Yepes.T, 2003,”Achieving the Millenium Development Goals : The Role of Infrastructure”*Policy Research Working Paper* World Bank, Washington DC.

[12] Bogetić .Z and Fedderke.J, 2006,”Forecasting Investments Needs in South Africa’s Electricity and Telecom Sectors,”*South African Journal of Economics,*vol74:3

[13] Calderon.C and Servén . L, 2008, ”Infrastructure and Economic Development in Sub-Saharan Africa,”*Policy Research Working Paper No 4712,*World Bank, Washington DC.

[14] Holland.M , 2017, ”Health impacts of coal fired power plants in South Africa, ”*Groundwork(South Africa)*

[15] Norregaard.J and Reppelin-Hill.V, 2000, ”Taxes and Tradable Permits as Instrument for Controlling Pollution: Theory and Practice,” *IMF Working Paper* WP/00/13.

[16] Heerden .J, Gerlagh.R, Blignaut.J,Horridge.M , Hess.S, Mabugu.R and Mabugu.M , 2006, ”Searching for Triple Dividends in South Africa: Fighting $C0_2$ pollution and poverty while promoting growth,” *IMF Working Paper* WP/00/13.

[17] Kamien, Morton.I and Schwartz.N, 1981, ”Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management,” New York: North-Holland

[18] Dorfman.R, 1969, ”An Economic Interpretation of Optimal Control Theory,” *The American Economic Review,* Vol. 59, pp. 817-831

[19] Buchanan. J, 1969, ”External Diseconomies, Corrective Taxes and Market Structure,” *American Economic Review*,Vol.59,pp. 139-47

[20] Requate.T, 1993, ”Pollution Control in a Cournot Duopoly via Taxes or Permits,”*Journal of Economics,*Vol.58, pp255-91

[21] Koustaal. P, 1997, ”Economic Policy and Climate Change: Tradable Permits for Reducing Carbon Emissions,” Cheltenham,UK: Edward Elgar

[22] Xepapadeas.A, 1997, ”Advanced Principles in Environmental Policy,” Cheltenham,UK: Edward Elgar

[23] Gaskins.D, 1970, ”Dynamic Limit Pricing: Optimal Pricing under Threat of Entry.” *Journal of Economic Theory* 3: 306-322

[24] Thisse.J.F, 1972, ”Un modele dynamique de la firme avec differenciation du prodiut” *Recherches Economiques de Louvain*,no.1, April, 3-16.

[25] Jacquemin,A.P, 1973, ”Optimal control and advertising policy.” *Metroeconomica 25,* 200-207.

[26] Horsky.D , 1977, ”Empirical analysis of optimal advertising policy .” *Management Science 23,* no.10,1037-1049.

[27] Bensoussan. A , Bultez.A and Naert. P , 1978, ”Leader’s dynamic marketing behavior in oligopoly, in: A. Bensoussan, P.R. Kleindorfer and C.S. Tapiero, eds,” *Applied optimal control(North-Holland , Amsterdam)*123-145.

[28] Gilbert.R , 1989, ”Mobility barriers and the value of incumbency.” *Handbook of Industrial Organization,* vol 1.North-Holland, Amsterdam , pp.475-535.

[29] Jamison.M,2005, ”Rate of Return: Regulation,”*Public Utility Research Center, University of Florida*

[30] Brock.W and Dechert .W , 1985, ”Dynamic Ramsey Pricing.” *International Economic Review* 26(3): 569-591

[31] Hamermesh.D and Pfann.G , 1996, ” Adjustment costs in Factor Demand.” *Journal of Economic Literature* XXXIV:1264-1292

[32] Zaccour.G, 2013, ”Differential Games in the Economics and Management of Pollution: A Tutorial,”*GERAD, HEC Montreal, Canada*

[33] Basar.T and Olsder.G, 1999, ”Dynamic Noncooperative Game Theory”*Classics in Applied Mathematics: 2nd Edition*

[34] Eliashberg.J and Steinberg. R, 1987, ”Marketing-production decisions in an industrial channel of distribution,”*Management Science,33(8):*981-1000

[35] Desai. V.S, 1992, ”Market-production decisions under independent and integrated channel structure, ” *Annals of Operations Research, 34:*275-306

[36] Desai. V.S, 1996,”Interactions between members of a marketing-production channel under seasonal demand,”*European Journal of Operations Research,90:*115-141

[37] Chintagunta.P and Jain.D, 2002, ”A dynamic model of channel member strategies for marketing expenditures,”*Marketing Science, 11(2):*168-188

[38] Frutcher. G and Messinger.P , 2003, ” Optimal management of fringe entry over time.” *Journal of Economic Dynamics and Control*28 pp 445-446.

[39] Kogan.K and Tapiero C.S, 2007, ”Supply Chain Games: Operations Management and Risk Valuation,”*Springer.*New York.

[40] He.X and Sethi S.P , 2008, ”Dynamic slotting and pricing decisions in a durable product supply chain.”*Journal of Optimization Theory and Applications 134(8)*

[41] Fanokoa .S.P , Telahigue.I and Zaccour G, 2010, ”Buying cooperation in an asymmetric environmental differential game,”*Journal of Economic Dynamics and Control*

[42] Novak.A.J , Feichtinger .G and Leitmann .G, 2010, ”A differential game related to terrorism: Nash and Stackelberg Strategies”

[43] Anorld. M and Narciso. G, 2008, ”Services Inputs and Firm Productivity in Sub-Saharan Africa: Evidence from Firm level Data,” *Journal of African Economies* 17(4)

[44] Bogetić. Z and Fedderke.W ,2006, ”Forecasting Investment Needs in South Africa’s Electricity and Telecommunications Sectors.” *South African Journal of Economics* Economic Society of South Africa,vol.74(3): 557-574

[45] Breeze. P, 2010, ”The Cost of Power Generation,” *Business Insights*

[46] Brock.W and Dechert. W , 1985, ”Dynamic Ramsey Pricing.” *International Economic Review* 26(3): 569-591

[47] Buchanan. J, 1969, ”External Diseconomies, Corrective Taxes and Market Structure,” *American Economic Review*,Vol.59,pp. 139-47

[48] Chiang. A, 1992, ”Elements of Dynamic Optimization.” Mcgraw-Hill. Inc

[49] Chisari. O and Kessides. I, 2009, ”Pricing Dynamics of Network Utilities in Developing Countries,” *Review of Network Economics*, vol(8) Issue 3 .

[50] Eberhard. A and Gratwick.K, 2011, ”IPP’s in Sub-Saharan Africa: Determinants of Success,”*Energy Policy*(39) 5541-5549

[51] Eberhard. A, Gratwick.K, Morella. E and Antmann P, 2016, ”Independent Power Projects in Sub-Saharan Africa.” *The World Bank*

[52] El-Hawary. M, 1995, ”Electrical Power Systems,” *John Wiley & Sons, Inc*

[53] El-Hawary. M. E and Mansour . S. Y, “Performance evaluation of parameter estimation algorithms for economic operation of power systems”, *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-101, pp. 574–82, 1982.

[54] Escribano. A, Gausch. J and Pena. J, 2009, ”Assessing the Impact of Infrastructure Quality on Firm Productivity in Africa,” *Africa Infrastructure Country Diagnostic*, The World Bank

[55] Gaskins. D, 1970, ”Dynamic Limit Pricing: Optimal Pricing under Threat of Entry.” *Journal of Economic Theory* 3: 306-322

[56] Gilbert. R, 1989, ”Mobility barriers and the value of incumbency .” *Handbook of Industrial Organization,* vol 1.North-Holland , Amsterdam , pp.475-535.

[57] Hamermesh. D and Pfann. G , 1996, ” Adjustment costs in Factor Demand.” *Journal of Economic Literature* XXXIV:1264-1292

[58] Heerden. J, Gerlagh. R, Blignaut.J, Horridge.M , Hess.S, Mabugu. R and Mabugu. M , 2006, ”Searching for Triple Dividends in South Africa: Fighting $C0_2$ pollution and poverty while promoting growth,” *IMF Working Paper* WP/00/13.

[59] Hemamalini .S and Simon .S.P, 2010, “Artificial bee colony algorithm for economic load dispatch problem with non-smooth cost functions”, *Electric Power Components and Systems,* Vol. 38, pp. 786–803

[60] Holland. M, 2017, ”Health Impacts of Coal Fired Power Plants in South Africa,” *Groundwork, Health Care Without Harm*

[61] Joseph. K. L , 2010, ”The Politics of Power: Electricity Reform in India,” *Energy Policy 38, 503-511*

[62] Koustaal.P, 1997, ”Economic Policy and Climate Change: Tradable Permits for Reducing Carbon Emissions,” Cheltenham, UK: Edward Elgar

[63] Mangasarian. O , 1966, ”Sufficient Conditions for the Optimal Control of Nonlinear Systems.” *SIAM Journal on Control* 4: 139-152

[64] Modise. D and Mahotas. V, 2009, ”The South African Energy Sector,” *Department of Energy*.

[65] Northeast Group, 2017, ”Electricity Theft and Non-Technical Losses: Global Markets, Solutions and Vendors,” *Northeast Group, LLC*

[66] Norregaard. J and Reppelin-Hill. V, 2000, ”Taxes and Tradable Permits as Instrument for Controlling Pollution: Theory and Practice,” *IMF Working Paper* WP/00/13.

[67] Pontryagin. L, Boltyanskii. V , Gamkrelidze .R and Mishchenko. E, 1962, ”The Mathematical Theory of Optimal Processes.” New York: Wiley

[68] Requate. T, 1993, ”Pollution Control in a Cournot Duopoly via Taxes or Permits,”*Journal of Economics,*Vol.58, pp255-91

[69] Shoults. R. R and Mead. M. M,1984, “Optimal estimation of piece-wise linear incremental cost curves for EDC”, *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-103, pp. 1432–1438.

[70] Smith. T, 2004, ”Electricity Theft: a comparative analysis,” *Energy Policy*

[71] Taylor. F. J and Huang C. J, 1977, “Recursive estimation of incremental cost curves”, *Computers and Electrical Engineering,*

[72] Theerthamalai. A and Maheswarapu.S,2010, ”An effective non-terative ”λ -logic based” algorithm for economic dispatch of generators with cubic fuel cost function,” *International Journal of Electrical Power and Energy Systems*,Vol 32,Issue 5 pp 539-542

[73] World Bank, 2008 , *Sustainable Infrastructure Action Plan.*

[74] World Energy Council, 2001, *Pricing Energy in Developing Countries.*

[75] Xepapadeas. A, 1997, ”Advanced Principles in Environmental Policy,”*Cheltenham,UK: Edward Elgar*

[76] Zivić M, Milacic . A and Krsulja. M, 2012, ”A simplified model of quadratic cost function for thermal generators,” *Annals and Proceedings of DAAAM International* vol 23 2

[77] Iozzi.A, 2001, ” Strategic Pricing and Entry Deterrence under Price-cap Regulation” *Journal of Economics,* Vol.74(2001),No.3, pp 283-300

[78] Coyne.C and Coyne. R, 2015, ” The Economics of Price Control,”*Flaws and Ceilings: Price Controls and the Damage They Cause.* IEA , UK

[79] Averch. H and Johnson .L, 1962, ”Behavior of the Firm Under Regulatory Constraint,” *The American Economic Review,* Vol. 52, No. 5, pp. 1052-1069

[80] Ndulu, B., S. O’Connell, R. Bates, P. Collier and C. Soludo ,2008a, ”The Political Economy of Economic Growth in Africa 1960-2000” Vol. 1, Cambridge: Cambridge University Press.

[81] Chisari. O and Kessides.I , 2009, ”Pricing Dynamics of Network Utilities in Developing Countries,” *Review of Network Economics*,vol(8) Issue 3.

[82] Fosu, A. K, R. Bates and A. Hoeffler , 2006, ”Institutions, Governance and Economic Development in Africa: An Overview,” *Journal of African Economies*, supplement, vol. 15(1), pages 1-9.

[83] Vogelsang.I and Finsinger.J, 1979, ”A Regulatory Adjustment Process for Optimal Pricing by Multiproduct Monopoly Firms.”*Bell Journal of Economics*10:157-71

[84] Sappington, D.E.M, 1980, ”Strategic Firm Behavior under a Dynamic Regulatory Adjustment Process.”*Bell Journal of Economics*11:360-72

[85] Sappington, D.E.M and Sibey,D.S,1992, ”Strategic Nonlinear Pricing under Price-cap Regulation.”*Rand Journal of Economics*23:1-19

[86] Armstrong.M and Vickers.J, 1993, ”Price Discrimination , Competition and Regulation”*Journal of Industrial Economics* XLI:335-59

[87] Bos.D and Nett.L , 1990, ”Privatization, Price Regulation, and Market Entry. An Asymetric Multistage Duopoly Model.”*Journal of Economics*51:221-57

[88] Law,P.J, 1997,”Welfare Effects of Pricing in Anticipation of Laspeyres Price-cap Regulation: An Example”*Bulletin of Economic Research*49:17-27.

[89] Foreman, R.D, 1995, "Pricing Incentives under Price-cap Regulation."*Information Economics and Policy*7: 331-51

[90] Vickers.J and Yarrow.G, 1991, "Economic Perspective on Privatization" *American Economic Asscociation* Vol.5, No.2,111-132

[91] Ndulu.B, O'Connell.S, Bates.R, Collier.P and Soludo.C ,2008a, " The Political Economy of Economic Growth in Africa 1960-2000" Vol. 1, Cambridge: Cambridge University Press.

[92] Littlechild.S, 1983, "Regulation of British Telecom's Profitability,"*Report to the Secretary of State Department, Department of Industry*London.

[93] Mathios A.D, Robinson.K, 1989, "The Impact of Alternative Forms of State Regulation of AT&T on Direct-Dial, Long-Distance Telephone Rates,"*Price-Cap Symposium,Rand Journal of Economics* 20 (No. 3, Autumn): 437–453.

[94] Tirole. J, 1988,"The Theory of Industrial Organization."*Cambridge, Mass:* MIT Press.

[95] Liston.C, 1993, "Price-Cap versus Rate of Return Regulation,"*Journal of Regualtory Economics* Vol.5, issue 1, 25-48

[96] Zhang. Y, Kirkpatrick. C and Parker.D, 2008, "Electricity Sector Reform in Developing Countries: An Econometric Assessment of the Effects of Privatization, Competition and Regulation" *Journal of Regulatory Economics* Vol 33,Issue 2,pp 159-178

[97] Vlahinić-Dizdarević. N, 2011, "The Effects of Privatization in Electricity Sector: The Case of Southeast European Countries,"

[98] Kessides. I, 2012, "The Impacts of Electricity Sector Reforms in Developing Countries"*The Electricity Journal*Vol 25, Issue 6,pp 79-88

[99] Ros. A, 1999, "Does Ownership or Competition Matter? The Effects of Telecommunications Reform on Network Expansion and Efficiency"*Journal of Regulatory Economics*Vol 15,Issue 1,pp 65-92

[100] Ramamurti.R, 1997, "Testing the Limits of Privatization-Argentine Railroads," *World Development,* 25(12), 1973-93

[101] Hawdon.D, 1996, "Performance of Power Sectors in Developing Countries-A Study of Efficiency and World Bank Policy using Data Envelopment Analysis,"*Surrey Energy Economics Centre Discussion* Paper 88.

[102] Galal .A, Jones.L, Tandon. P and Vogelsang.I, 1994, "Welfare Consequences of Selling Public Enterprises-An Empirical Analysis" The World Bank

[103] Boubakri .V and Cosset .J.C , 1998, ”The Financial and Operating Performance of Newly Privatized Firms: Evidence from Developing Countries”*Journal of Finance,*53(3), 1081-1110.

[104] Delfino.A and Casarin .A , 2001, ”The Reform of the Utilities Sector in Argentina,”*United Nations University World Institute for Development Economics Research Discussion Paper No. 2001/74,* June.

[105] Torero.M and Rekve.P, 1998, ”Privatization in Developing Countries: Lessons to be Learnt from the Mozambican Case,” *Transformation,*No.36,pp.73-92

[106] Dewenter.K.L and Malatesta .P.H, 2001, ”State-Owned and Privately-Owned Firms: An Empirical Analysis of Profitability, Leverage, and Labor Intensity,”*American Economic Review,*91(1), 320-335.

[107] Bortolotti.B, Fantini.M and Siniscalco. D, 1998.”Regulation and Privatization: the Case of Electricity,”*Working Paper, Department of Economics and Finance,*University of Turin.

[108] Pollit.M.G, 1997, ”The Impact of Liberalization on the Performance of the Electricity Supply Industry: An International Survey,”*The Journal of Energy Literature,* 3(2),3-31

[109] Macedo.R,2000, ”Privatization and the Distribution of Assets in Brazil,”*Washington DC.: Inter-American Development Bank Research Department.*

[110] Parker. D, 2002,”Economic Regulation: A Review of Issues”*Annals of Public and Co-operative Economics,*73(4)

[111] Vickers.J and Yarrow.G, 1998, ”Privatization : An Economic Analysis,”*London-Cambridge MA, The MIT Press*

[112] Lee.J.D, Park.S and Kim.T, 1999, ”Profit, Productivity, and Price Differential: An International Performance Comparison of the Nature Gas Transportation Industry,”*Energy Policy*

[113] Villalong .B, 2000,”Privatization and Efficiency: Differentiating Ownership Effects from Political , Organizational, and Dynamic Effects,”*Journal of Economic Behaviour & Organization,*42,43-74

[114] Estache. A, 2000, ”In Infrastructure for Development: Private Solutions and the Poor,”*World Bank and ECARES, Universite Libre de Bruxelles*

[115] Wood.R, 2004,”The Privatization of Public Utilities:What are the Gains? Why the Popular Opposition?” *unpublished manuscript*

[116] Paredes.M,2001, "Redistributive Impact of Privatization and the Regulation of Utilities in Chile." *World Institute for Development Economics Research*

[117] Wallstein. S,2001,"An Econometric Analysis of Telecom Competition, Privatization, Regulation in Africa and Latin America"

[118] Garrigou. A,2017, "The impacts of bringing electricity to rural and vulnerable populations,"*The Beam*

[119] World Bank,2017b, "State of Electricity Access Report," *Washington: World Bank*

[120] Scott.A,2017, "Why Wait? Seizing the Energy Access Dividend,"*Sustainable Energy for All and Power For All*

[121] Tallapragada.P, Shkaratan.M, Izaguirre.A, Helleranta.J,Rahman.S and Bergman.S, 2009, "Monitoring Performance of Electric Utilities: Indicators and Benchmarking in Sub-Saharan Africa"*World Bank*

[122] Matenga.Z, Fedderke.J and Terpenny.J, 2018, "Pricing Dynamics of Electricity in Privatized Markets with Underdeveloped Networks" *under review Energy Economics*

[123] Asad.E, 2008, "Challenges of Data Collection in Developing Countries-The Pakistani Experience as a Way Forward," *Statistical Journal of the IAOS*Vol.25,no.1,2,pp.11-17

[124] Peng. H, 2013, " Optimal Subsidy policy for accelerating the diffusion of green products" *Journal of Industrial Engineering Management,* JIEM,2013-6(2):626-641

[125] Norregaard.J and Reppelin-Hill.V, 2000, "Taxes and Tradable Permits as Instrument for Controlling Pollution: Theory and Practice," *IMF Working Paper* WP/00/13.

[126] Spence .M, 1976, "Product differentiation and welfare."*The American Economic Review* Vol.66, No.2 pp 407-414

[127] Saaty . T.L., 1980, “The Analytic Hierarchy Process.” McGraw-Hill, New York.

[128] Luthra S, Kumar S, Garg D and Haleem A, 2015, "Barriers to renewable/sustainable energy technologies adoption: Indian perspective. " *Renew Sustain Energy Rev.* 41(Supplement C):762–76

[129] Polzin F, Migendt M, Täube FA, von Flotow P, 2015, "Public policy influence on renewable energy investments—A panel data study across OECD countries. " *Energy Policy.* 80(Supplement C):98–111.

[130] Sen.S and Ganguly.S, 2017, " Opportunities, barriers and issues with renewable energy development – A discussion. " *Renew Sustain Energy Rev.* 69(Supplement C):1170–81.

[131] Jogernson . S and Zaccour . G, 1999, " Price Subsidies and Guaranteed Buys of a New Technology." *European Journal of Operational Research,* 114(2), 338-345.

[132] Cantono .S and Silverberg,.G,2009, "A Percolation Model of Eco-Innovation Diffusion: The Relationship Between Diffusion, Learning Economies and Subsidies." *Technological Forecasting & Social Change,* 76(4), 487-496.

[133] Lorentziadis. P.L. and Vournas .S.G ,2011 , " A Quantitative Model of Accelerated Vehicle- Retirement Induced by Subsidy." *European Journal of Operational Research,* 211(3), 623-629.

[134] Raschen.M, 2015, "An End to Energy Subsidies in Developing Countries and Emerging Markets – If not now, then when? "*KFW Economic Research* No.89

[135] Zhang . F and Gallagher . K .S, 2016, "Innovation and technology transfer through global value chains: Evidence from China's PV industry." *Energy Policy.*;94(Supplement C):191–203.

[136] World Bank Group, 2017, " State of Electricity Access Report," *World Bank Group*

[137] Wier. M, Birr-Pedersen. K, Jacobsen. H. K,and Klok. J, 2005. "Are CO2 taxes regressive? Evidence from the Danish experience." *Ecological Economics*52(2), 239–251.

[138] Grainger. C. A and Kolstad. C. D., 2010. "Who Pays a Price on Carbon?"*Environmental and Resource Economics* 46(3), 359–376

[139] Fullerton. D and Heutel. G, 2010, "Analytical General Equilibrium Effects of Energy Policy on Output and Factor Prices." *The B.E. Journal of Economic Analysis & Policy* 10(2).

[140] Fullerton. D, Leicester. A, and Smith. S, 2010. "Environmental Taxes." *In Institute for Fiscal Studies (IFS), Dimensions of Tax Design,* pp 423 - 518. Oxford University Press.

[141] Combet.E, Ghersi. F, Hourcade.J.C,and Thiery. D, 2010, "Carbon Tax and Equity The importance of Policy Design." *Critical Issues in Environmental Taxation* Vol. VIII, pp. 277–295.

[142] Poterba. J. M, 1991, "Is the Gasoline Tax Regressive?" *Tax Policy and the Economy,* Vol 5, pp. 145–164.

[143] Metcalf. G. E., Paltsev. S, Reilly, J. M., Jacoby. H. D.and Holak, J., 2008, "MIT Joint Program on the Science and Policy of Global Change Tax Proposals." *MIT Joint Program on the Science and Policy of Global Change* (160).

[144] Metcalf. G. E, 1999, ”A Distributional Analysis of Green Tax Reforms.” *National Tax Journal* L II(4).

[145] Sterner. T, 2011. ”Fuel Taxes and the Poor: The Distributional Effects of Gasoline Taxation and Their Implications for Climate Policy.” Johns Hopkins University Press.

[146] Bento. A. M., Goulder. L. H., Henry. E., Jacobsen. M. R, Haefen. R. H. V, 2005, ”Distributional and Efficiency Impacts of Gasoline Taxes : An Econometrically Based Multi-market Study.” *American Economic Review* 95(2), 282–287

[147] Bento. A. M, Goulder. L. H, Jacobsen. M. R,and Haefen, R. H. V., 2009, ”Distributional and Efficiency Impacts of Increased US Gasoline Taxes.” *American Economic Review* 99(3), 667–699.

[148] Parry.I, Norregaard .J and Heine.D,2012, ”Environment Tax Reform: Principles from Theory and Practice”*Annual Reviews of Resource Economics*

[149] Metcalf. G. E., Paltsev. S, Reilly, J. M., Jacoby. H. D.and Holak, J., 2008, ”MIT Joint Program on the Science and Policy of Global Change Tax Proposals.” *MIT Joint Program on the Science and Policy of Global Change* (160)..

[150] Fosu. A. K, R. Bates and Hoeffler.A , 2006, ”Institutions, Governance and Economic Development in Africa: An Overview,” *Journal of African Economies*, supplement, vol. 15(1), pages 1-9.

Appendix A: Chapter 1

Lemma 9 *(Necessary and Sufficient Condition) if* $\beta_e = \beta_d$ *,* $P_e > P_d \implies \dot{N}_d > 0$

Proof. Since $\beta_e = \beta_d$, then $\eta_d = 1$ but $\frac{P_e}{P_d} > 1$, therefore $\frac{P_e}{P_d} > 1$ ■
We have, $P_e > P_d$, when $\beta_e = \beta_d$. The intuition is immediate; consumers prefer joining a network where the prices are lower.

Lemma 10 *(Necessary and Sufficient Condition) if* $\beta_e > \beta_d$ *,* $P_e > P_d \implies \dot{N}_d > 0$

Proof. Since $\beta_e > \beta_d$, we have $\eta_d > 1$ thus $\frac{1}{\eta_d} < 1$
Also $\frac{P_e}{P_d} > 1$, therefore $\frac{P_e}{P_d} > \frac{1}{\eta_d}$ ■

Lemma 11 *(Sufficient Condition) if* $\beta_e < \beta_d$ *,* $P_e > P_d \implies \dot{N}_d > 0$

Proof. Since $\beta_e < \beta_d$, we have $\eta_d < 1$ thus $\frac{1}{\eta_d} > 1$
Also $\frac{P_e}{P_d} > 1$, therefore $\frac{P_e}{P_d} > \frac{1}{\eta_d}$ ■
If $P_e > P_d$, it is counterintuitive that we can have , $\dot{N}_d < 0$, but this means that the price ratio $1 < \frac{P_e}{P_d} < \frac{1}{\eta_d}$. Thus $P_e > P_d$ is a sufficient condition but not necessary to experience network increase for the incumbent firm when its price elasticity of demand is greater than the price elasticity of demand of the entrant's market, but $\frac{P_e}{P_d} > \frac{1}{\eta_d}$ is sufficient and necessary condition for network growth for the incumbent firm. The intuition is that, the incumbent firm has to set a price level that accounts for the ratio of the price elasticity of demand in its market to that of the entrant's market.

Lemma 12 *There exists* $\beta_e < \beta_d$ *and* $P_e > P_d$ *such that* $\dot{N}_d < 0$

Proof. Since $P_e > P_d$, Let $p = \frac{P_e}{P_d} \in (1,\infty)$, we have $b = \frac{1}{\eta_d} \in (1,\infty)$ thus $\exists p$ such that $p < b$ hence $\frac{P_e}{P_d} < \frac{1}{\eta_d}$. Therefore $\dot{N}_d < 0$. ■
From (1), $\dot{N}_d < 0$ when $\beta_e P_e < \beta_d P_d$ which means $\frac{P_e}{P_d} < \frac{1}{\eta_d}$. This is a necessary and sufficient condition. We analyze three possible condition, (a)$\beta_e = \beta_d$ (b) $\beta_e > \beta_d$ and (c) $\beta_e = \beta_d$.

Lemma 13 *(Necessary and Sufficient Condition) if* $\beta_e = \beta_d$ *,* $P_d > P_e \implies \dot{N}_d > 0$

Proof. Since $\beta_e = \beta_d$, then $\eta_d = 1$ but $\frac{P_e}{P_d} < 1$, therefore $\frac{P_e}{P_d} < 1$ ■
We have, $P_d > P_e$, when $\beta_e = \beta_d$. The intuition is immediate; consumers prefer joining a network where the prices are lower.

Lemma 14 *There exists* $\beta_e > \beta_d$ *and* $P_d > P_e$ *such that* $\dot{N}_d < 0$

Proof. Since $P_d > P_e$, Let $p = \frac{P_e}{P_d} \in (0,1)$, we have $b = \frac{1}{\eta_d} \in (0,1)$ thus $\exists p$ such that $p < b$ hence $\frac{P_e}{P_d} < \frac{1}{\eta_d}$. Therefore $\dot{N}_d < 0$. ■

Lemma 15 *(Sufficient Condition) if* $\beta_e < \beta_d$ *,* $P_e < P_d \implies \dot{N}_d < 0$

Proof. Since $\beta_e < \beta_d$, we have $\eta_d < 1$ thus $\frac{1}{\eta_d} > 1$
Also $\frac{P_e}{P_d} < 1$, therefore $\frac{P_e}{P_d} < \frac{1}{\eta_d}$ ■

If $P_e > P_d$, it is counterintuitive that , $\dot{N}_d < 0$, but this means that the price ratio $1 < \frac{P_e}{P_d} < \frac{1}{\eta_d}$. Thus $P_d > P_e$ is a sufficient condition but not necessary to experience network decrease for the incumbent firm when its price elasticity of demand is greater than the price elasticity of demand of the entrant's market, but $\frac{P_e}{P_d} < \frac{1}{\eta_d}$ is sufficient and necessary condition for network decrease for the incumbent firm. The intuition is that, the entrant firm can find a pricing level that accounts for the ratio of the price elasticity of demand in its market to that of the incumbent market and cause a negative rate of change of the incumbent's network size.

Lemma 16 *There exists $\beta_e < \beta_d$ and $P_e > P_d$ such that $\dot{N}_d < 00$*

Proof. Since $P_e > P_d$, Let $p = \frac{P_e}{P_d} \in (1, \infty)$, we have $b = \frac{1}{\eta_d} \in (1, \infty)$ thus $\exists p$ such that $p < b$ hence $\frac{P_e}{P_d} < \frac{1}{\eta_d}$. Therefore $\dot{N}_d < 0$. ■

Appendix B: Chapter 3

Figure 7.1: **Frequency Graph for Energy Imports**

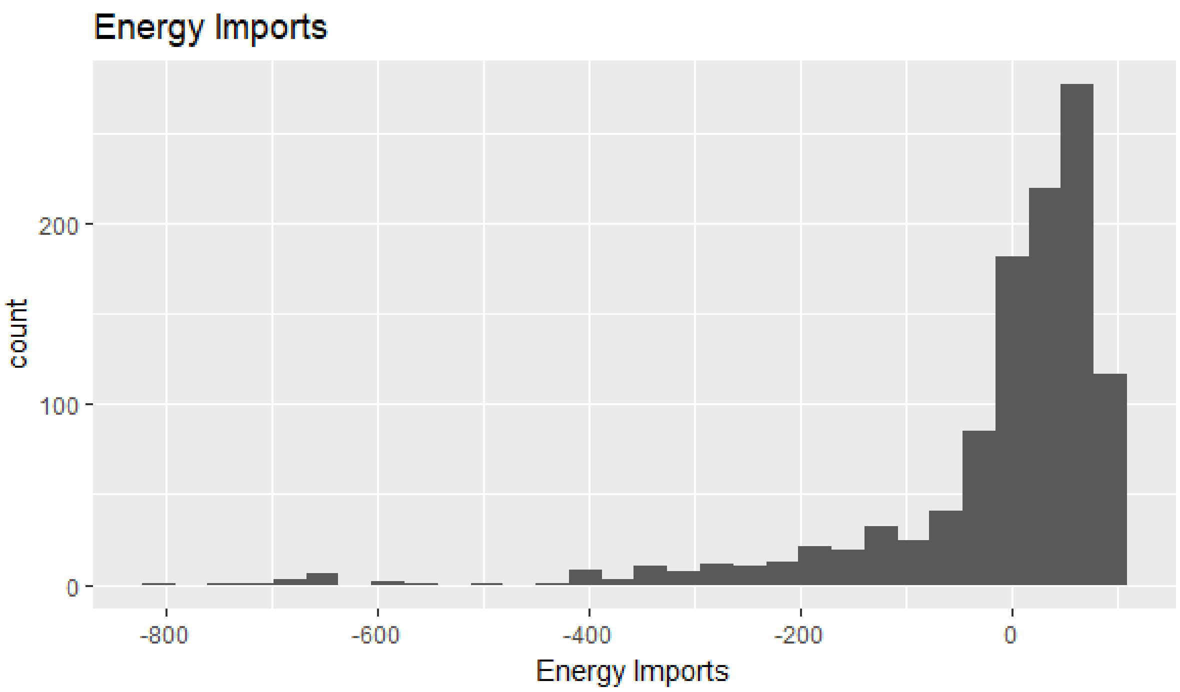


Figure 7.2: **Frequency Graph for Renewable Energy**

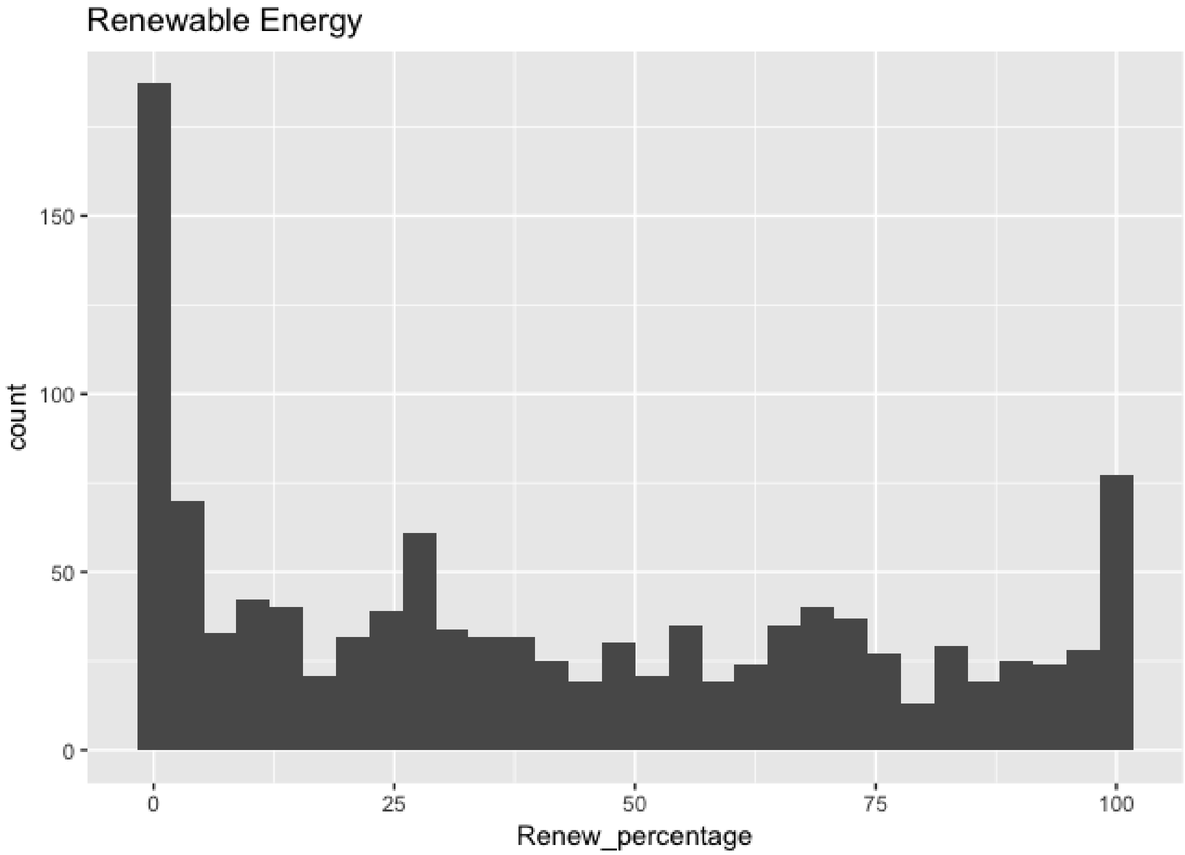


Table 7.1: Countries

Africa	Latin America	Europe	Middle East and North Africa
Botswana	Argentina	Austria	Algeria
Cameroon	Brazil	Belarus	Egypt
Cote d'Ivoire	Bolivia	Belgium	Morroco
Ghana	Chile	Croatia	Oman
Kenya	Costa Rica	Denmark	Tunisia
Malawi	Colombia	Finland	Turkey
Mauritius	Dominican Republic	Hungary	
Mozambique	Ecuador	Latvia	
Nigeria	Guatemala	Lithuania	
Senegal	Jamaica	Poland	
Tanzania	Mexico	Romania	
Uganda	Panama	Slovenia	
South Africa	Paraguay	Sweden	
Zambia	Peru		
Zimbabwe	Uruguay		
	Venezuela		

Table 7.2: National Population Access

	Dependent variable:		
	Nat_perc		
	(1)	(2)	(3)
Mono1	-4.904^{***}		4.943^{*}
	(1.699)		(2.877)
Priv1		6.417^{***}	9.579^{***}
		(1.330)	(2.270)
CPI	-0.067^{**}	-0.076^{***}	-0.088^{***}
	(0.028)	(0.028)	(0.028)
Renew_perc	-0.106^{***}	-0.110^{***}	-0.109^{***}
	(0.015)	(0.015)	(0.015)
Urb_Pop_Perc	0.132^{***}	0.120^{***}	0.108^{**}
	(0.046)	(0.046)	(0.046)
Cons_Capita	0.098	0.098	0.103
	(0.064)	(0.063)	(0.063)
Short_term_Debt	0.184^{***}	0.190^{***}	0.186^{***}
	(0.050)	(0.050)	(0.050)
log(Income_per_Capita)	8.159^{***}	8.362^{***}	8.590^{***}
	(0.748)	(0.737)	(0.748)
Ener_Impo	-0.016^{***}	-0.015^{***}	-0.016^{***}
	(0.005)	(0.005)	(0.005)
regionLatin America and Caribbe	0.693	1.085	0.873
	(1.558)	(1.541)	(1.544)
regionMiddle East and North Africa	3.355^{*}	3.959^{**}	3.372^{*}
	(1.927)	(1.881)	(1.909)
regionSub-Saharan Africa	-28.619^{***}	-27.885^{***}	-30.063^{***}
	(2.487)	(2.143)	(2.488)
Observations	951	951	951
R^2	0.802	0.805	0.805
Adjusted R^2	0.794	0.797	0.798
F Statistic	336.309^{***} (df = 11; 915)	343.107^{***} (df = 11; 915)	315.432^{***} (df = 12; 914)

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table 7.3: Descriptive statistics-SSA

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Ener_Impo	323	1.2	49.1	−137.7	−16.1	30.0	84.5
Rural_perc	350	22.3	27.0	0.001	3.7	28.4	100.0
Urb_perc	375	62.8	24.7	0.01	41.3	84.0	100.0
Nat_perc	375	36.0	26.7	0.01	13.7	51.5	99.4
Renew_perc	375	56.4	36.8	0	24.5	94.5	100
Cons_Capita	324	16.4	10.7	0.0	9.0	20.7	74.0
Syst_Loss	324	16.4	10.7	0.0	9.0	20.7	74.0
CPI	336	66.1	37.5	0.2	38.0	96.1	205.6
Short_term_Debt	375	10.7	9.8	0.0	3.2	16.0	57.1
Income_per_Capita	375	1,215.3	1,583.1	68.5	285.0	1,111.3	8,276.1
Urb_Pop_Perc	375	36.3	13.3	11.1	25.7	44.7	66.4
Long_term_Debt	375	0.03	0.04	0.0	0.01	0.04	0.3

Table 7.4: Descriptive statistics-Europe

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Ener_Impo	325	47.4	28.0	−65.7	33.2	66.0	92.7
Rural_perc	325	100.0	0.0	100	100	100	100
Urb_perc	325	100.0	0.0	100	100	100	100
Nat_perc	325	100.0	0.0	100	100	100	100
Renew_perc	325	28.0	24.7	0.05	2.7	49.7	81.1
Cons_Capita	325	9.8	5.7	3.4	5.4	12.4	46.6
Syst_Loss	325	9.8	5.7	3.4	5.4	12.4	46.6
CPI	297	75.7	28.5	0.02	66.5	97.5	114.9
Short_term_Debt	325	4.4	13.2	0	0	0	80
Income_per_Capita	299	16,800.3	14,152.6	792.6	4,426.7	25,143.9	53,696.2
Urb_Pop_Perc	325	69.4	13.8	50.4	58.0	83.2	97.8
Long_term_Debt	325	0.01	0.02	0	0	0	0

Table 7.5: Descriptive statistics-MENA

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Ener_Impo	150	−121.0	242.1	−807.9	−277.4	67.1	90.9
Rural_perc	133	86.0	21.4	10.2	84.6	98.3	100.0
Urb_perc	133	98.2	2.9	84.7	97.7	99.8	100.0
Nat_perc	133	92.7	11.8	48.1	91.9	99.2	100.0
Renew_perc	150	9.7	11.7	0.0	0.6	16.9	46.2
Cons_Capita	150	13.1	4.2	1.5	10.4	15.9	22.2
Syst_Loss	150	13.1	4.2	1.5	10.4	15.9	22.2
CPI	140	71.5	32.2	0.1	52.6	94.8	142.1
Short_term_Debt	150	10.5	9.0	0.0	1.4	17.8	35.8
Income_per_Capita	150	3,258.7	2,719.4	526.1	1,336.6	3,989.4	13,284.6
Urb_Pop_Perc	150	60.2	10.1	42.7	53.4	67.8	80.1
Long_term_Debt	150	0.05	0.04	0.0	0.02	0.1	0.2

Table 7.6: Descriptive statistics-LAC

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Ener_Impo	299	−35.6	114.2	−361.0	−124.4	58.6	90.3
Rural_perc	300	79.8	18.8	10.4	73.4	93.8	100.0
Urb_perc	300	97.6	3.2	82.1	96.0	99.8	100.0
Nat_perc	300	91.3	9.9	56.4	88.9	98.2	100.0
Renew_perc	300	51.7	28.9	2.2	26.2	74.1	99.2
Cons_Capita	300	15.5	5.8	0.0	11.0	19.5	36.0
Syst_Loss	300	15.5	5.8	0.0	11.0	19.5	36.0
CPI	257	64.9	40.7	0.001	33.2	94.5	348.2
Short_term_Debt	300	12.3	8.9	0	6.0	18.4	45
Income_per_Capita	300	3,996.8	2,770.4	601.3	1,982.7	5,267.8	14,451.5
Urb_Pop_Perc	300	70.1	14.2	42.0	58.1	84.2	91.4
Long_term_Debt	300	0.04	0.03	0	0.02	0.1	0

VITA

Zvikomborero A. Matenga

Zvikomborero Alexander Matenga was born and raised in, Glen Norah A, a high density suburb of Harare. He also spent a big part of his life in Buhera in rural Zimbabwe. He attended Zuvarabuda Primary School and later attended Harare High School. He graduated from Harare High school in 2008. Zvikomborero continued his education at Wesleyan University in Connecticut, where he graduated with degrees in Mathematics and Chemistry. At Wesleyan University, he worked under the mentorship of Dr. Albert Fry studying computational organic electrochemistry. Zvikomborero began graduate school in August of 2015 at The Penn State University, and began working under the tutelage of Dr. Janis Terpenny and Dr. Johannes Fedderke investigating policy work in electricity markets in developing economies.